Contagious Cargo: Health Externalities from Livestock Trade during Early Globalization *

Grant Goehring†

May 7, 2026

Abstract

Trade requires the movement of goods across space, which increases the risk of disease transmission. When such externalities are significant, trade restrictions may improve welfare. I examine a nineteenth-century episode of globalization to assess the effectiveness of trade restrictions in mitigating health externalities. By the 1870s, Britain was importing over a million live animals annually. Officials associated these imports with animal disease outbreaks and responded with a series of trade restrictions. I find that import bans on European sheep to curb foot-and-mouth disease in the early 1890s inadvertently increased outbreaks of sheep scab, a mite-borne disease, among domestic sheep. This increase was driven by a shift toward new trading partners, primarily in the Americas, where sheep scab was highly prevalent. The import bans also had negative economic effects by increasing the price of meat in British cities and reducing wool production. I then build a model with domestic livestock production, trade, and disease transmission to assess the overall welfare effects of alternative trade policies. The calibrated model indicates that banning European sheep reduced welfare relative to a scenario in which imports continued despite a moderate foot-and-mouth disease risk. The episode highlights the importance of understanding equilibrium spillovers across goods and diseases when designing trade restrictions to address externalities.

*I am grateful to Bob Margo, James Feigenbaum, and David Lagakos for guidance throughout the project. I also thank Yong Cai, Martin Fiszbein, Claudia Goldin, Walker Hanlon, Eric Hilt, Kevin Lang, Yuhei Miyauchi, Dev Patel, Vasudha Ramakrishna, Natalia Ramondo, Hannah Rhodenhiser, and Johannes Schmieder as well as seminar participants at Boston University, Colgate University, Harvard University, UC Davis, UC Merced, the University of South Carolina, the NBER DAE Summer Institute meetings, the Economic History Association, and the Economic History Society for helpful comments and conversations. I also gratefully acknowledge funding from the Gates Foundation Pre-doctoral Fellowship on Gender in the Economy, awarded through the National Bureau of Economic Research.

†Goehring: Boston University. Email: grant.goehring@gmail.com

1 Introduction

A central idea in economics is that trade improves welfare by allowing countries with different comparative advantages to specialize. While the movement of goods across space is innocuous in many contexts, there are instances where trade can lead to various externalities. For example, the trade in agricultural products can lead to health or environmental externalities as diseases, pests, or invasive species are transported across locations. This gives rise to a tradeoff that is inherent to the trade in these goods where potential economic gains might come at the cost of disease transmission. Overall, the trade in agricultural products, where this externality is most salient, was a sizable 8% of total merchandise trade in 2023.[1] Understanding ways to effectively address the risks associated with trading these goods has important economic implications for many countries.

Governments recognize the risks associated with the trade in agricultural products and often enact trade restrictions on imports. The recent US response to an outbreak of screwworm in Mexico is a useful illustration of how governments implement trade barriers to prevent health externalities. Screwworm, a parasitic fly that lays eggs in open wounds of cattle, multiplies rapidly as successive generations hatch. This results in the death of the host in a matter of weeks. With no effective treatment, the fly poses a major threat to livestock. Once eradicated in the United States, screwworm has migrated northward from South America as warmer temperatures expand its range. In November 2024, the US government prohibited imports of live cattle from Mexico to prevent the fly from entering the United States.[2] While such trade barriers might have negative economic effects by raising the prices of animal products domestically, they might improve overall welfare by reducing the risk of widespread pest or disease outbreaks that would negatively impact domestic agriculture.

This paper explores the effectiveness of trade restrictions aimed to address health and environmental externalities from trade. I examine the historical trade in live animals during the first age of globalization in the late nineteenth century to both empirically and theoretically assess the health and economic consequences of trade restrictions aimed to reduce the spread of animal diseases. A key contribution of this paper is to highlight that trade restrictions are not guaranteed to solve health externalities. Their effectiveness depends crucially on the policy's design, and how the policy interacts with economic incentives and the underlying disease environment. Trade restrictions can have important equilibrium effects in contexts with multiple diseases that may transmit across species.

[1] A link to the Food and Agriculture Organization discussing the size of the trade in agricultural products can be found here.

[2] The following article summarizes the current risks associated with the cattle trade and the spread of screwworm: "Avian Flu Wiped Out Poultry. Now the Screwworm Is Coming for Beef." *New York Times*, July 28, 2025. A link to the article can be found here.

In the 1840s, Britain began removing tariffs that had effectively prohibited imports of a variety of agricultural products (Irwin, 1989; O'Rourke, 1997; Heblich et al., 2024). In the subsequent decades, several European countries started exporting over a million live animals to Britain annually, where they were often slaughtered for domestic consumption. These animals had to be transported live because refrigeration technologies that would have allowed them to be slaughtered prior to being shipped did not exist at the time (Zimmerman, 1962). British officials began linking trade in live animals to disease outbreaks among domestic livestock. The most severe of these episodes was an outbreak of rinderpest, a highly contagious and lethal disease, in 1865 that was imported from Russian cattle that killed approximately 6% of all domestic cattle in Britain. Parliament responded to the outbreak by passing a series of laws allowing British officials to regulate live animal imports and impose trade restrictions for the purposes of preventing disease transmission from foreign animals to domestic livestock. In subsequent decades, rinderpest and foot-and-mouth disease, two diseases that could transmit between species, motivated several trade restrictions by the British government.

This paper examines the consequences of trade restrictions implemented by the British on live sheep imports in the last quarter of the nineteenth century due to concerns that imported sheep were infected with foot-and-mouth and rinderpest. The primary trade restriction I study is the prohibition of European sheep imports that started with a ban on German sheep in 1889 and was extended to all continental European countries in 1892. I also analyze a second, less severe policy adopted at various times that required imported sheep to be slaughtered at the port of entry. This half measure allowed domestic consumers to still benefit from animal imports while reducing the likelihood foreign animals would contact domestic livestock. The first two empirical parts of the paper assess the health and economic effects of the restrictions using a difference-in-differences empirical strategy. The last part develops a model to illustrate how health externalities can reduce the gains from trade and analyze the welfare effects of various policies the British could have chosen.

There are several features of this context that make it particularly useful for examining health externalities from trade and the effectiveness of trade restrictions in addressing them. First, these trade restrictions were implemented in a data-rich environment. One contribution of the paper is to digitize a variety of historical data on disease, trade, and domestic agricultural production. As part of the effort to prevent disease spread, the British government collected detailed data on the number of outbreaks of several diseases among domestic animals. Officials also recorded the number of infected imported animals arriving at ports. I digitize these data, making it feasible to assess how domestic disease changed in response to the trade restrictions and link domestic disease outbreaks to infected imported animals. The

primary disease I will focus on is sheep scab – a mite-borne disease that damages the skin and wool of sheep – because data on the disease is available spanning several decades around the trade restrictions. I also digitize data on foot-and-mouth disease, an important disease that motivated many of the trade restrictions adopted by British officials. The government also kept records of the trade in live animals and conducted annual agricultural censuses that provide information on the number of domestic livestock, which I digitize to complement the information on disease transmission. A second useful feature of the context is that the trade restrictions on sheep imports were implemented during a few key episodes between 1877 and 1892. This makes it possible to use a difference-in-differences empirical strategy to assess changes in outcomes before and after the trade restrictions were implemented. A final useful feature is that these restrictions were implemented as globalization was just starting to make health externalities from trade a consequential problem that governments needed to address. Therefore, this provides a particularly useful setting where the effects of trade restrictions can be estimated relative to the preexisting, largely laissez-faire, equilibrium. Whereas in the modern context, it is difficult to isolate the effects of trade restrictions given that existing trade agreements govern how countries can address disease risk from trade.

The paper starts by documenting changes in trade patterns in response to the restrictions. Before the import ban on European sheep, about 75% of Britain's sheep imports were exported from Germany and the Netherlands. The ban on European imports in 1889 forced British consumers to seek new trading partners. Between 1888 and 1895, the share of imported sheep from the Americas – primarily the United States, Canada, and Argentina – increased from approximately 10% to over 90% of total sheep imports. This trade substitution had important implications for disease transmission. After the import ban, the share of imported sheep infected with sheep scab increased from less than 1% in 1888 to 8% in 1895. In contrast, an earlier policy requiring sheep from key European trading partners to be slaughtered at the port of entry did not lead to substantial changes in trade patterns or disease among imported animals.

The next part presents the main empirical results on how the trade restrictions impacted disease transmission among domestic sheep. To assess the ban on European sheep, I use a difference-in-differences empirical strategy comparing the number of sheep scab outbreaks in counties closer to the main ports where sheep were imported to counties further away, before and after the ban. The results suggest that sheep scab outbreaks increased by approximately 45% after the ban. This is consistent with the trade substitution patterns in which Britain started to import sheep from countries with significantly higher prevalence of sheep scab after the import ban. The results from an event study specification suggest sheep scab outbreaks continue to worsen until 1896 which corresponds exactly with when Britain required port

slaughter of sheep from the United States and Canada. This provides additional evidence linking high prevalence of disease among imported sheep from the Americas to disease transmission among domestic sheep in Britain. While the ban on European sheep increased the prevalence of sheep scab among domestic sheep, it was effective at keeping foot-and-mouth disease out of Britain. I also find that the earlier episode where port slaughter was required for continental Europe in 1877 was effective at reducing sheep scab outbreaks.

The last empirical section turns to the economic effects of the trade restrictions. I focus on two main outcomes: the price for meat paid by domestic consumers and wool production. To analyze meat prices, I digitize data from historical newspapers on meat prices in London and Liverpool around the ban on German sheep imports in 1889 and the policy mandating port slaughter on European sheep in 1877. Since it is likely that internal movement of livestock would equalize prices across regions in response to the trade restrictions, I do not use geographic variation to assess effects on prices. Instead, I use an empirical strategy that compares the price of mutton (sheep) to the price of beef before and after each policy was implemented. Given that the trade restrictions only targeted sheep and not cattle, we would expect the price of mutton to be differentially affected by the restrictions as long as mutton and beef were not perfect substitutes. In London and Liverpool, Mutton prices increased by approximately 10% and 6% relative to beef prices in the months after the import ban on German sheep. In contrast, there was no change in meat prices in response to the 1877 port slaughter policy.

The second economic effect I analyze is how the ban on European sheep affected wool production. Wool was an important industry for Britain both to export as a raw material and to process into textiles and clothing products (Bowden, 1956). It is also possible that the ban affected wool production due to the increase in sheep scab among domestic sheep. Sheep scab has significant negative effects on a sheep's ability to produce wool as the mites cause skin complications (Rehbein et al., 2000). While data on wool production is not available during the period, data on wool exports is available for various ports throughout Britain. I show that wool exports decline at ports near counties in Britain that experienced higher sheep scab infection after the ban on European sheep. This provides evidence consistent with the higher prevalence of sheep scab caused by the ban also reducing wool production among domestic sheep.

In summary, the empirical portion of the paper shows that the import ban on European sheep led to a change in Britain's trading partners that increased sheep scab infection among domestic flocks. It also had negative economic effects by increasing the price of meat for domestic consumers and reducing domestic wool production. However, the ban was effective at keeping foot-and-mouth disease out of Britain, one of the ban's primary objectives.

This episode highlights the importance of policy design when implementing trade restrictions to address health externalities given potential downstream general equilibrium forces. The results also highlight how less strict policies can be effective at mitigating the health externalities from trade. The 1877 port slaughter policy reduced sheep scab infections among domestic sheep and did not increase meat prices since the same exporters were still allowed to export animals for immediate slaughter.

Motivated by these facts, the last section develops a simple model combining domestic livestock production and consumption, international trade, and elements from an epidemiological model in which imported animals can spread disease to domestic livestock. A key use of the model is to assess the welfare implications of various trade policy scenarios, especially given that the trade restrictions influenced multiple diseases at once. In the model, a domestic household owns cattle and sheep, and consumes beef, wool, and mutton that is produced from these livestock. There are two diseases, one that can only infect sheep (sheep scab) and another that can transmit between species, capturing the important inter-species aspect of foot-and-mouth. The domestic country can import sheep from exporting countries at the risk of importing sheep with either disease that can potentially infect domestic livestock.

I calibrate the model using the data I digitized for the empirical analysis as well as other information from the history, epidemiology, and veterinary literature. I then use the calibrated model to compare the welfare implications of different trade policies. Steady state welfare is approximately .9% higher with free trade relative to autarky which shows that the model exhibits the basic Ricardian idea of gains from trade. However, when I introduce a health externality in which 3% of imported sheep are infected with sheep scab, the welfare gain relative to autarky declines to .3%. I then analyze a counterfactual that resembles the ban Britain implemented on European sheep. In this scenario, the imported sheep now have a higher rate of sheep scab, capturing the substitution to sheep from the Americas, while still having no foot-and-mouth infection. Welfare in this counterfactual is .7% worse than autarky. I then compare this scenario to an alternative policy the British could have adopted where they continued to allow imported sheep from Europe. This would have kept sheep scab prevalence at pre-ban levels, yet increased the prevalance of foot-and-mouth disease among imported sheep that could infect domestic livestock (both sheep and cattle). In this scenario welfare is only .1% worse than autarky. This suggests that the ban implemented by Britain may have been worse overall than continuing to allow trade with Europe. However, in a counterfactual in which rinderpest is the second disease that could be imported from Europe, welfare is 2.9% worse than autarky due to the disease's severity and virulence. Overall, the model highlights how the welfare effects of trade restrictions depend on the underlying disease environment and how this interacts with trade incentives.

This study contributes to several strands of literature. First, it relates to a large literature spanning agricultural economics, environmental economics, and ecology exploring the consequences of trade spreading animal diseases, pests, and invasive species. Work in ecology focuses on the threat of invasive species due to trade (e.g. Costello and McAusland, 2003; McAusland and Costello, 2004; Margolis et al., 2005; Perrings et al., 2005; Costello et al., 2007; Olson, 2006; Westphal et al., 2008; Jardine and Sanchirico, 2018; Hulme, 2021). A large body of work in agricultural economics focuses on the threat of foot-and-mouth disease infecting livestock, motivated by periodic outbreaks of the disease over the last several decades (Berentsen et al., 1992; Paarlberg and Lee, 1998; Bicknell et al., 1999; Ekboir et al., 2002; Paarlberg et al., 2003; Zhao et al., 2006; Rich and Winter-Nelson, 2007; Knight-Jones and Rushton, 2013; Ito et al., 2023; Kappes et al., 2023). Most of the previous work is focused on either documenting the costs of externalities associated with trade or theoretically examining how trade restrictions, or other eradication efforts, might address the externalities. This paper differs by providing empirical evidence on the effectiveness of trade restrictions at addressing health externalities. I show that the effectiveness of trade restrictions depends on the policy's design and the underlying disease environment.

This paper also relates to several parts of the literature on international trade. There is a growing body of work highlighting ways in which various protective policies, such as industrial policy or protective tariffs, may improve welfare over free trade (Irwin, 2000; Costinot et al., 2015; Juhász, 2018; Goldberg et al., 2024; Juhász and Steinwender, 2024; Bartelme et al., 2025; Lane, 2025). However, within the trade literature, there is little working illustrating how trade restrictions might be welfare improving due to trade-induced health externalities. The exception is Antràs et al. (2023) which studies the relationship between trade and pandemics theoretically by building a trade model that incorporates disease transmission across countries. The mechanism by which disease spreads in their model is by individuals traveling between countries to foster business relationships. There is also a small empirical literature exploring the link between commerce and disease spread (Oster, 2012; Adda, 2016). This idea has a long history dating back at least to the bubonic plague outbreak in the fourteenth century that spread from Asia to Europe via trade routes (Benedictow, 2004; Yue et al., 2017). A key distinction is that this literature focuses on people spreading disease by moving goods across space, whereas in this study the movement of the good itself causes the health externality. I also examine the effectiveness of trade restrictions in addressing these externalities.

Lastly, this paper contributes to several parts of the literature within economic history. First, it relates to the large literature examining the rise of globalization in the nineteenth century (O'Rourke and Williamson, 1994; O'Rourke et al., 1996; O'Rourke, 1997; O'Rourke

and Williamson, 2001, 2002; Obstfeld and Taylor, 2004; Jacks, 2005, 2006; Jacks et al., 2010; Hanlon, 2015; Steinwender, 2018; Heblich et al., 2024). Overall, the literature focuses on the economic benefits from this episode of globalization, although a large component of it discusses the distributional consequences of trade. In contrast, this study highlights a downside associated with the rise in trade. This study also relates to the seminal work in economic history by Olmstead and Rhode (2002, 2004, 2007, 2015) exploring the consequences of animal diseases throughout United States history and the political economy of policies used to combat them. This study complements this work by focusing explicitly on the international trade dimensions of animal diseases in the historical context.

The rest of the paper proceeds as follows. Section 2 presents additional historical background on the livestock trade, animal diseases, and the trade restrictions used to address them. Section 3 briefly summarizes the various data that was digitized for the empirical analysis. Section 4 uses this data to provide a series of descriptive facts on how trade patterns changed after the trade restrictions. Section 5 presents the main empirical results on how the trade restrictions affected disease transmission among domestic sheep. Section 6 then turns to how the trade restrictions affected economic outcomes, focusing on meat prices and wool production. Section 7 develops a simple model and calibrates it to perform welfare assessments of different trade policies. Section 8 concludes.

2 Background

This section presents historical background on the setting of the paper. It will focus on three main elements: the British meat industry in the nineteenth century, the international trade in animals for domestic consumption, and the British response to animal diseases spread from trade.

The Industrial Revolution in the late eighteenth century led to an increase in the British standard of living. Higher incomes facilitated changes in the British diet as more individuals could afford more diverse food, including meat. The population in Britain was growing during the period which increased the demand for agricultural products. Britain was also land scarce relative to other European and North American countries which made it difficult to expand the production of livestock to meet domestic demand (Perren, 2017). All of these factors put upward pressure on the price of food in the early nineteenth century. Britain implemented a series of trade liberalization policies in the 1840s that made it feasible to import agricultural goods from abroad. The most famous of these policies was repealing the Corn Laws that removed tariffs on cereal grains making it economically viable to import grains (O'Rourke, 1997; Heblich et al., 2024). However, similar policies in the 1840s opened

the British economy to a broader set of agricultural imports which made it feasible to import foreign livestock. Britian's high standard of living and relative land scarcity led to a thriving international trade in livestock in the ensuing decades.[3]

Until the late-1870s, the lack of effective refrigeration technology made it difficult to slaughter livestock in the exporting country before transporting the meat to consumers in Britain (Perren, 1971). Meat would often spoil if animals were slaughtered before transit, especially during the long transatlantic voyage from Canada or the United States. This meant that in the early decades of the international livestock trade, animals had to be transported live to Britain before being slaughtered. Figure B1 provides images drawn by the *London Illustrated News* in 1865 that depict the transport of animals. Panel (a) shows cattle onboard a Dutch ship in transit to London and panel (b) shows animals being processed upon arrival at the Metropolitan Cattle Market in London. While only illustrations, the images capture some of the risks associated with the trade. Animals often faced poor conditions in transit. Ship owners had incentives to load as many animals as possible onto the ships. For instance, when describing the transatlantic trade, the *National Livestock Journal* wrote, "Cattle are taken on and under deck in stalls measuring 2'8" on vessels sailing from New York." In stalls less than three feet in diameter, cattle had very little space to move and were often fixed in place for the entire voyage. The close proximity of animals during transit, as well as at the ports of entry in Britain, created an environment where disease could spread among animals.

The first major disease outbreak after trade liberalization occurred in 1865 when imported cattle infected with rinderpest landed in Hull. Rinderpest was a particularly serious disease during the period because it was both highly contagious and fatal. Between the summer of 1865 and early 1867 the "Cattle Plague", as rinderpest was known to contemporaries, spread throughout Britain ravaging domestic livestock. Figure B2 presents data compiled by Parliament on the number of weekly infections and deaths during the epidemic. At the height of the outbreak, over 18,000 cattle were infected weekly and a similar magnitude were dying from the disease or from slaughtering to curtail the spread. By the end of the outbreak over 278,000 cattle were infected and nearly 290,000 cattle died or were killed. The number of deaths is approximately 6% of the total number of domestic cattle in Britain in 1866. The Cattle Plague of 1865-67 highlights the potential health externalities associated with globalization as goods move across space. It also precipitated a series of policy responses by British officials in the following decades, including the trade restrictions on animal imports analyzed in the empirical section.

Building on legislation passed during the Cattle Plague, the Contagious Diseases (Ani-

[3]The summary of the British meat industry and trade in livestock presented in this section draws heavily from Perren (1978).

mals) Act of 1869 (hereinafter CDAs) gave the Privy Council broad powers to regulate live animal imports. Under the CDAs, the Privy Council had the power to implement two main trade restrictions. First, it could require animals imported from specific exporting countries to be slaughtered at the port of entry. This half measure allowed animals to still be imported, but prohibited them from being transported within Britain for fattening or to be sold at inland markets. Exporters from countries subjected to port slaughter were required to slaughter the animals within 10 days of arrival and could only land animals at particular ports designed to handle imported animals. The Privy Council changed which ports were eligible to handle these animals over time. The second main tool at the Privy Council's disposal was outright import bans. Trade restrictions were applied to the exporter-animal pair – for example German sheep or Canadian cattle – depending on the perceived risk of disease spread. In addition to the trade restrictions, the Privy Council also employed a team of veterinarians that were tasked with inspecting imported animals at the ports of entry. If animals were found to be infected they were often slaughtered to prevent disease spread.[4]

The CDAs mandated the Privy Council to address particular animal diseases – including rinderpest, farcy, contagious bovine pleuropneumonia, and sheep scab – the latter of which will be the focus in the empirical section. Parliament also extended the list of animal diseases under the Privy Council's mandate in response to disease outbreaks. For instance, foot-and-mouth disease was added after a severe outbreak in 1877. There were several biological aspects of these diseases that made it difficult for the Privy Council to effectively combat them. First, many of these diseases – such as foot-and-mouth disease or rinderpest – could be transmitted across species. As will be discussed in the next section, trade restrictions affecting sheep were often implemented because of the risk that sheep would spread diseases to cattle. Second, some diseases could be spread asymptomatically or had long incubation periods (Olmstead and Rhode, 2004). Therefore, even perfectly conducted medical inspections by veterinarians at the ports of entry might not have been fully effective at preventing the spread of diseases to domestic livestock. This could rationalize other types of trade restrictions, such as port slaughter or outright bans, to combat disease transmission.

2.1 Trade Restrictions on Sheep Imports

This section briefly summarizes the main trade restrictions studied in the empirical section. The key trade restriction episodes targeting sheep were motivated by fears of rinderpest or foot-and-mouth disease among imported animals. Both diseases led to worse health outcomes for cattle than sheep. However, sheep could transmit the disease to other sheep as well as

[4] Perren (1978, p.107-114) provides a useful summary of the various powers given to the Privy Council by Parliament to combat the spread of animal diseases.

between species to cattle. Since sheep generally suffered milder symptoms, there was a greater risk that infected imported sheep would not show signs of infection during medical examinations at the port of entry and therefore spread the diseases to domestic animals.

The first major restriction on sheep imports into Britain occurred in 1877 when the Privy Council required sheep from several European countries to be slaughtered at the port of entry. These restrictions were enacted after a German ship arrived in London on January 15 carrying cattle that exhibited symptoms consistent with rinderpest. The *Annual Report of the Veterinary Department* summarized the event, "Mr. Holmans, the inspector, was present; and his attention was attracted to the animals in consequence of the extremely wretched appearance which they presented. One of them indeed died on the landing-place, and others were in a dying state."[5] Subsequent examinations confirmed that cattle onboard were infected with both rinderpest and foot-and-mouth disease. The Privy Council responded swiftly and proactively to prevent a wider outbreak similar to the Cattle Plague of 1865. They culled the infected animals at the London port and incinerated the bodies to prevent further infection. Since foot-and-mouth and rinderpest could transmit from sheep to cattle, they also required imported sheep from five European countries – Belgium, France, Germany, the Netherlands, and Russia – to be slaughtered at the port of entry. Port slaughter maintained access to foreign sheep for domestic consumption while trying to prevent disease spread to foreign livestock.

The primary trade restriction assessed in the empirical section is a series of complete bans on European sheep imports that rolled out starting in 1889. Sheep imported from Germany were banned first in 1889 after sheep from several German ports were found to have foot-and-mouth disease when examined at British ports. Foot-and-mouth disease had for the most part been successfully eliminated in Britain during the 1880s which prompted officials to act swiftly and ban German sheep to prevent the disease from spreading among domestic livestock.[6] Like rinderpest, foot-and-mouth disease could spread across species of hoofed animals. While the disease is highly contagious, the mortality rate from foot-and-mouth disease is much lower than rinderpest. In the subsequent years, foot-and-mouth disease spread from Germany to other European countries prompting British officials to implement a ban on sheep from all continental European countries in 1892.[7]

[5]The *Annual Report of the Veterinary Department of the Privy Council* (1877, pg. 8-12) provides a summary of the events that resulted in the port slaughter trade restrictions.

[6]Figure A8 presents foot-and-mouth infections among domestic animals (panel a) and imported sheep (panel b) over time. The figure shows that before the import bans, Britain had successfully eradicated foot-and-mouth among domestic livestock by the mid-1880s.

[7]Norway and Iceland were the only European countries with significant livestock exports that were not banned. The geographic isolation of these countries shielded them from the outbreak of foot-and-mouth disease originating in Germany. For more discussion of the rationale behind the import ban see: *Annual Report of the Director of the Veterinary Department for the Year 1892, pg. 6.*

The final restriction I examine is a series of port slaughter policies implemented in the years after the ban on European sheep. Because of the substitition to sheep from the Americas after the ban on Europe, Britain subjected American and Canadian sheep to port slaughter in 1896. Port slaughter was made universal in 1897 which required all animals imported into Britain to be slaughtered upon entry. Before this policy, the Privy Council's trade restrictions were primarily implemented country-by-country. They were aimed at specific types of animals from particular exporters (see Figure B3).

3 Data

This section describes the main data used in the empirical parts of the paper. I digitize data on the livestock trade, animal disease transmission, and domestic agriculture from a variety of historical sources. Appendix A provides additional details on the data and examples of the reports from which the data were digitized.

Animal Disease Data: To assess the health effects of the trade restrictions, I digitize data on animal infections that were compiled in the annual reports of the Veterinary Department of the Privy Council. As mentioned in Section 2, the Privy Council was tasked by Parliament to combat the spread of specific animal diseases such as rinderpest, CBPP, foot-and-mouth disease, and sheeps scab. Local authorities were required to report outbreaks of these diseases to the Privy Council. For some of these diseases, the Privy Council compiled detailed county-level data on the number of disease outbreaks among domestic animals in its annual reports. Figure A1 provides an example of the county-level data I digitize for sheep scab which is the main disease I will focus on in the empirical analysis. The annual reports include information on the number of known outbreaks as well as the number of total sheep infected, making it possible to study both the extensive and intensive margins. In many respects, this data is more detailed than data on human health during the period. For example, data on infections that did not result in mortality was not systematically collected during the period in Britain. The data collected by the Privy Council makes it possible to study disease transmission that does not ultimately result in mortality. I will focus on the number of outbreaks as the outcome of interest because the annual reports suggest the number of outbreaks was reported more accurately than the number of infected sheep. Many farmers could easily identify an outbreak of the disease on their farm whereas checking all animals for signs of infection was a much more difficult task. I digitize the data for all counties in England, Scotland, and Wales from 1873 to 1902 which covers a period before and after each of the major trade restrictions on sheep imports.

The annual reports also contain information on infections among imported animals. As

part of the Privy Council's attempts to combat the spread of animal diseases, it required all imported live animals to be inspected at the port of entry. Infected animals were normally slaughtered immediately to prevent further contagion. The annual reports provide detailed data on the number of animals infected with a particular disease from specific exporting countries. Figure A2 provides an example showing the number of animals infected with sheep scab that were imported into Britain. I digitize this data to help understand the mechanisms behind changes in disease transmission when the trade restrictions were implemented.

Livestock Trade Data: I collect two final pieces of information from the annual reports related to the trade in live animals. First, the annual reports keep track of the exact date trade restrictions are levied against particular exporting countries. Figure B3 displays the variation in when the Privy Council implemented trade restrictions at the animal-exporter level. Second, I collect information on animal imports into Britain over time. The trade data compiled in the annual reports is remarkably detailed tracking imports at the animal-port-exporter level. So for each animal type (cattle, sheep, and swine) the data report the number of animals imported from a particular exporting country to a specific port within Britain. Figure A3 provides an example of the trade data. I digitize this data annually from 1873 to 1902 to examine compositional changes in the trade over time and understand locations within Britain that were more geographically exposed to imported animals.

Domestic Livestock Data: I supplement this data with information on the number of domestic livestock contained in Britain's agricultural censuses, the *Agricultural Returns of Great Britain*. A nice feature of the British agricultural census is that it was conducted annually, in contrast to the decadal census in the United States, and therefore provides higher frequency data on the supply of domestic livestock. Figure A4 provides an example from the census showing the number of animals by county. I digitize the number of sheep and cattle at the county-level annually from 1866 to 1902.

Prices and Production Data: Finally, to analyze the economic effects of the trade restrictions, I digitize data on meat prices and wool exports. I digitize monthly data on the price of mutton (sheep) and beef in London and Liverpool from *The Times* to assess whether consumers faced higher meat prices after the restrictions. Figure A5 provides an example of the newspaper data. Sheep scab also affected the quality and quantity of wool that sheep produced. While to the best of my knowledge wool production data is not available during the period, data on the amount of wool exported at British ports does exist. I digitize this data around the ban on European sheep from the *Annual Statement of the Trade of the United Kingdom*.

4 Effects of the Trade Restrictions on Trade Patterns

This section presents descriptive facts related to the trade in live sheep and highlights the compositional change in exporters after Britain implemented the import bans on European countries. These facts will help inform modeling choices in the conceptual framework section. They also motivate how treatment will be defined in the empirical section examining how the trade restrictions affected disease transmission.

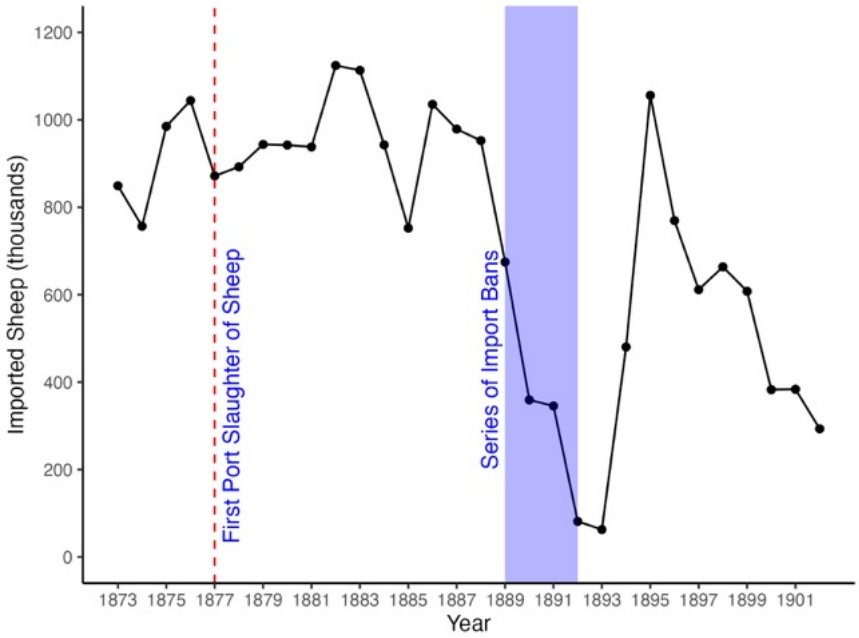
Figure 1 presents data on sheep imports to Britain over time digitized from the Veterinary Department annual reports. Panel (a) plots the total number of imported sheep. From 1873 to the start of the import bans Britain imported approximately one million sheep a year. Starting in 1889, when Britain banned German sheep imports due to the risk of foot-and-mouth disease infection, the number of imported sheep began to decline. Imported sheep continued to decline in subsequent years as Britain expanded the ban to include all continental European countries in 1892. By 1893, imports were approximately 7% of the pre-ban total in 1888. Figure A7 panel (b) shows that the magnitude of imported sheep relative to the stock of domestic sheep was also quite steady over time. The number of imported sheep was approximately 3-4% of the size of the domestic stock. This number decreased significantly after the import bans started in 1889. Overall, the bans on European sheep led to a large reduction in the aggregate number of sheep imported to Britain. After 1893, imports rebounded as consumers shifted to sheep from the Americas. However, the trade in live sheep declined steadily afterwards as refrigerated meat became a larger part of the market around 1900.

Panel (b) of Figure 1 highlights the compositional change in the countries exporting to Britain after the import bans. The figure plots the share of total sheep imports from the main European exporters (Germany and the Netherlands) and the main exporters from the Americas (the United States, Canada, and Argentina) over time. Germany and the Netherlands represented approximately 75% of the total imports until the bans that prohibited them from exporting to Britain. The share is steady over time and does not change significantly during other trade restrictions, such as the policy in 1877 which required German and Dutch sheep to be slaughtered at the port of entry. After the bans on continental European imports, the countries in the Americas become the primary exporters to Britain. By 1895, the United States, Canada, and Argentina account for over 90% of total sheep imports.

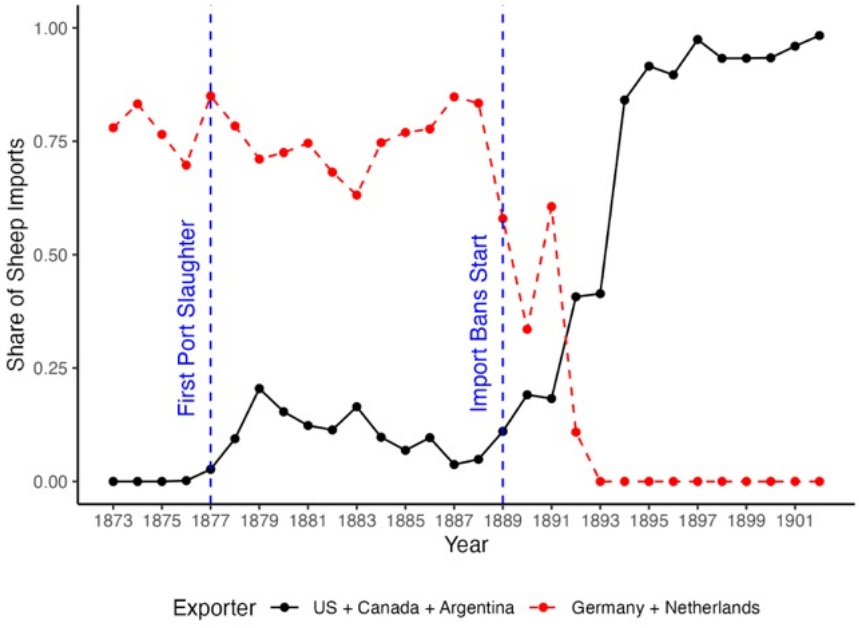
The shift in the countries exporting to Britain after the import ban also led to a change in the ports where sheep were imported. Figure 2 shows the number of sheep imported into each port before and after the import bans were implemented. The white bars display the number imported at each port in 1888 just prior to the import bans. The vast majority

Figure 1: Sheep Imports to Britain Over Time

(a) The Number of Imported Sheep



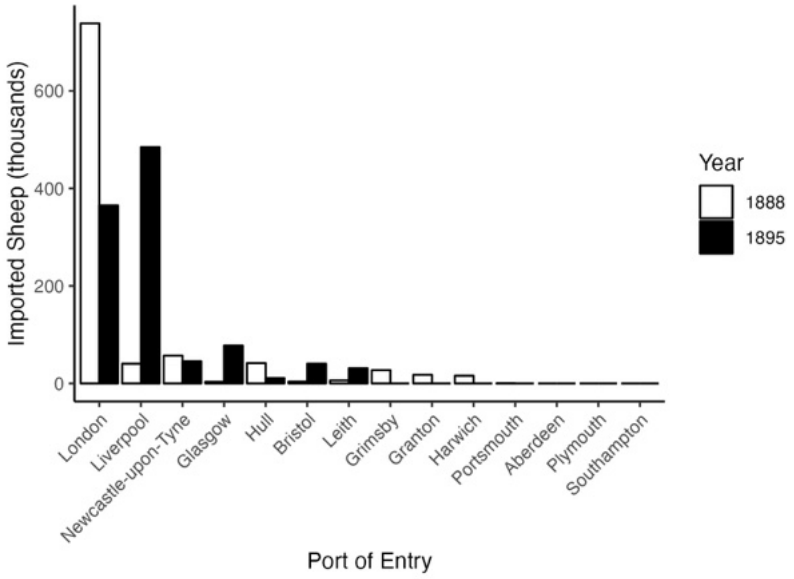
(b) The Share of Total Imports for the Main Exporters



Note: This figure provides information on sheep imports to Britain over time. Panel (a) displays total sheep imports over time. Panel (b) displays the share of total sheep imports represented by the two key groups of exporters. The black, solid line displays the share of total imports comprised of sheep from the United States, Canada, and Argentina. The red, dashed line displays the share of total imports comprised of sheep from Germany and the Netherlands. The data are taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*.

of sheep were imported to London. The black bars show the number imported in 1895 several years after the imports bans were in effect. By 1895 the number of sheep imported into Liverpool was similar in magnitude and actually exceeded the number imported into London. This likely reflected the relative geographic proximity of Liverpool to Britain's new trade partners in the Americas. The empirical strategy in Section 5 will use the fact that sheep imports were geographically concentrated in Liverpool and London to assess the effects of the import bans on disease transmission.

Figure 2: Location of Sheep Imports Before & After the Import Bans on European Sheep



Note: This figure shows the ports where sheep were imported within Britain. The white bars display the number in 1888, the last year before import bans on European sheep started. The black bars show the number in 1895, several years after the bans when countries in the Americas became the largest exporters to Britain. The data are taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*.

An important consequence of the trade substitution away from Europe is that the new sheep from the Americas had significantly higher prevalence of sheep scab. As part of the broader set of policies to reduce the spread of disease, British officials employed veterinarians to examine animals for infection at the ports of entry. Figure 3 panel (a) presents data on the number of imported animals with sheep scab for a long time span. In the years immediately prior to the import bans there were very few imported sheep that were infected with sheep scab. The number of imported sheep with infections increased significantly in the years after the bans. Panel (b) shows that the increase in infected sheep was driven by sheep from Britain's new trading partners in the Americas. Figure A9 shows that share of sheep that were infected also increased from less than 1% prior to the ban to approximately 8% in 1895

before declining in subsequent years.

5 The Health Effects of Trade Restrictions

This section presents the main results on how the trade restrictions affected disease transmission. The primary focus will be on the effect of the sheep import bans that were implemented between 1889 and 1892. The second part will examine the health effects of the less severe port slaughter policies that were implemented before and after the import bans.

5.1 Effects of the European Sheep Import Bans

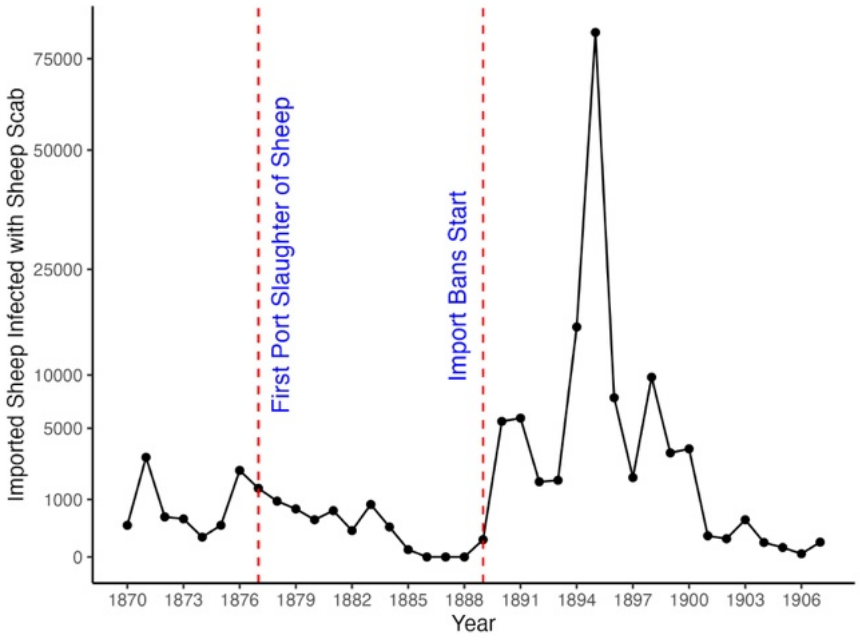
This section assesses how the import bans on European sheep affected the spread of animal diseases. As discussed in Section 2, Britain implemented a series of import bans starting in the late 1880s because German sheep inspected at the ports were found to be infected with foot-and-mouth disease. This led the Privy Council to ban German sheep imports on March 22, 1889. As foot-and-mouth disease spread from Germany to other European countries, the ban was extended to all continental European countries in 1892.

To study how the trade restrictions affected animal disease transmission, I will focus primarily on sheep scab. Relative to other common diseases during the period, sheep scab is not as fatal, although it is highly contagious. It is a mite-borne disease that directly impacts a sheep's skin and wool. As the mites reproduce and spread, it can cause more serious health effects and negatively impact fertility. There are several features of the context that makes focusing on sheep scab useful for identification purposes. First, unlike some other animal diseases, the Veterinary Department collected detailed data at the county-level on the number of sheep scab outbreaks for the entire sample period. Second, the trade restrictions on sheep imports were mainly implemented in two distinct episodes: the mandatory port slaughter policies in 1877 and the import bans between 1889 and 1892. In contrast, the restrictions on cattle were much more staggered throughout the 1870s and 1880s as the Privy Council responded to new information regarding the disease environments in particular exporting countries (see Figure B3). The fact that the restrictions on sheep imports are implemented during two distinct periods provides clean episodes where I can use a difference-in-differences empirical strategy to assess the effects of the trade restrictions on disease transmission. Therefore, it is advantageous to focus on a disease that impacted sheep, such as sheep scab.

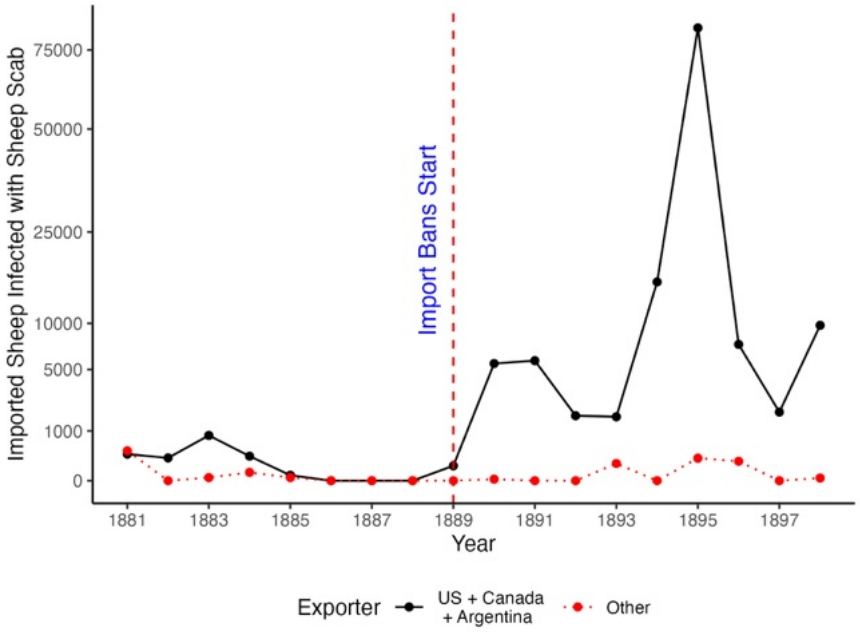
A final useful feature of focusing on sheep scab is that it affected sheep and not other commonly imported animals. Some of the other diseases that the Privy Council was tackling, such as rinderpest and foot-and-mouth disease, could transmit between species. Since the

Figure 3: The Number of Imported Sheep Infected with Sheep Scab Over Time

(a) Total Imported Sheep Infected with Sheep Scab



(b) Total Imported Sheep Infected with Sheep Scab by Country



Note: This figure displays the number of imported sheep found to be infected with sheep scab at the ports of entry in Britain. Panel (a) displays the total number of infected imported sheep over time. The dashed vertical lines indicate the years when the trade restrictions were implemented. Panel (b) displays the total number of infected sheep by exporting country around the period where import bans on European sheep were enacted. The black, solid line displays the number of infected sheep from the United States, Canada, and Argentina. The red, dashed line shows the number of infected sheep from all other exporting countries. The data are taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*.

Privy Council adopted policies regulating the cattle trade as well, disentangling the effect of sheep-specific restrictions on these other diseases is challenging. Focusing on sheep scab does not have this limitation given that it only affected sheep.

To assess how the trade restrictions affected animal disease transmission, I use a difference-in-differences empirical strategy that exploits the geographic variation in where sheep were imported in the years around the import bans. Figure 2 displays the ports where sheep were imported just prior to the bans as well as several years afterwards when the substitution to new trading partners in the Americas had occurred. The vast majority of imports were concentrated in Liverpool and London. The empirical strategy will compare disease transmission in counties closer to Liverpool and London to those further away, before and after the implementation of the trade bans. The assumption behind this approach is that counties geographically closer to where sheep were imported would be more impacted by changes in trade policy than more distant counties.

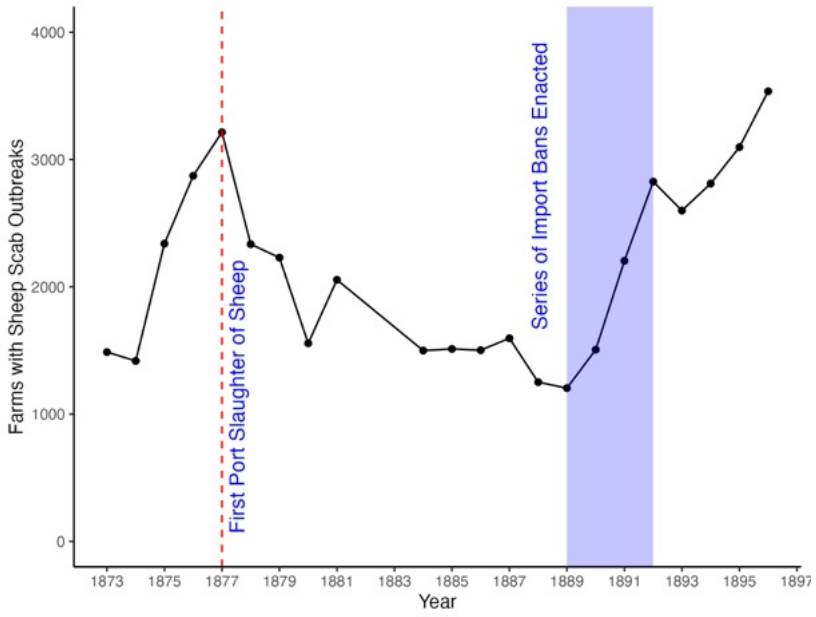
The estimating equation is:

$$outbreaks_{ct} = \alpha + \beta post_t \times proximity_c + \alpha_c + \alpha_t + \epsilon_{ct} \tag{1}$$

Where $outbreaks_{ct}$ is the number of sheep scab outbreaks in county c in year t. $post_t$ is an indicator equal to 1 for years after 1888, the period when Britain began implementing import bans, and 0 otherwise. $proximity_c$ is an indicator for whether county c is below the median minimum distance to either London or Liverpool. These were the primary locations where the banned European sheep as well as the new sheep from the Americas were imported. Therefore, this specification will capture both the effect of removing exposure to European sheep as well as the effect of domestic sheep being exposed to imported sheep from exporters in the Americas as Britain sought new trade partners. Lastly, α_c and α_t are county and year fixed effects, respectively. In order to assess potential pre-trends and dynamic effects over time, I will also use an event study approach where $post_t$ is replaced with year fixed effects.

Before turning to the regression results, Figure 4 presents the descriptive data on the aggregate number of sheep scab outbreaks across Britain over time. A first notable feature is that throughout the 1880s, in the years before the import bans, the number of outbreaks was declining. Outbreaks then increased in subsequent years after the import bans were implemented. This provides descriptive evidence that the bans had the unintended effect of increasing disease transmission. A second notable feature is that the first mandatory port slaughter policy on several European countries that was implemented in 1877 coincides with a reduction in outbreaks which provides suggestive evidence that the port slaughter policy was effective at reducing disease transmission. I will assess the port slaughter policy more formally in the next section.

Figure 4: Total Domestic Sheep Scab Outbreaks In Britain Over Time

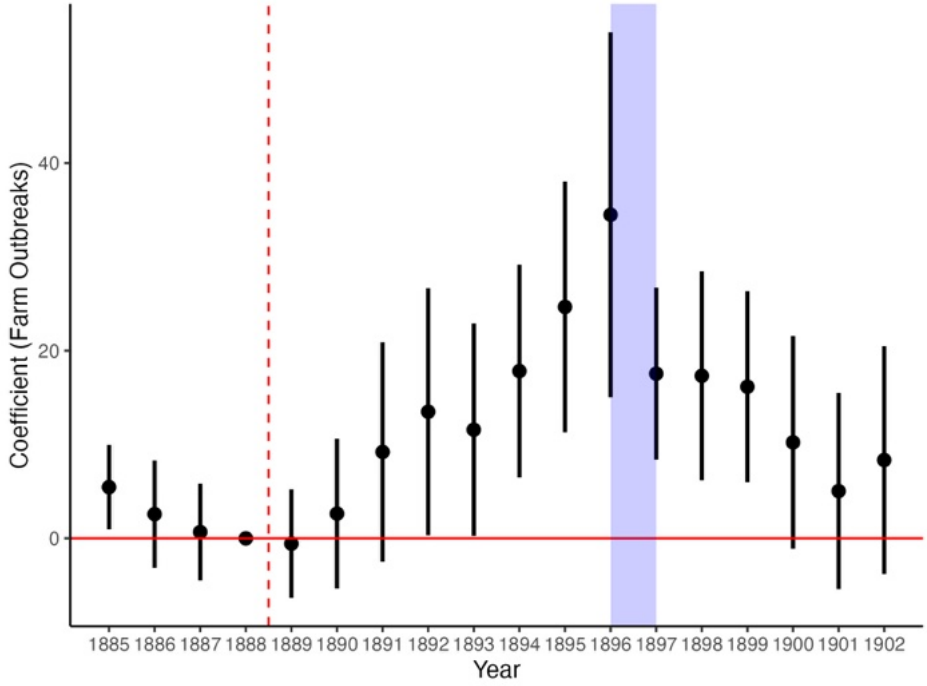


Note: This figure plots the total number of sheep scab outbreaks across all British counties over time. The red, dashed vertical line corresponds to the year when the first set of port slaughter trade restrictions on sheep imports were implemented. The blue, shaded rectangle corresponds to the period where a series of permanent import bans on sheep from continental European countries were enacted. The data are taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*.

Figure 5 presents the main event study results from estimating equation (1) where the outcome is the number of annual sheep scab outbreaks on farms at the county-level. In the years prior to the start of import bans in 1889, counties closer to ports where sheep were commonly imported had similar disease dynamics to counties further away. If any pattern exists, outbreaks were declining in areas closer to ports importing sheep. The number of sheep scab outbreaks increased in years after import bans start to be enacted. The effects grew over time until 1897 which corresponds with when a series of port slaughter policies were first enacted on Canadian and US sheep in 1896 and then universally on all imported animals from all exporting countries at the beginning of 1897. I will discuss this port slaughter policy as well in the next section.

Table 1 presents the results from estimating equation (1) where the outcome is the number of sheep scab outbreaks. Column 1 presents the baseline difference-in-differences estimate of the effect of the import bans on the number of farm outbreaks for the entire sample period from 1885 to 1902. This estimate corresponds to the average effect from the event study in Figure 5. It implies that the import bans led to 11 more sheep scab outbreaks in counties closer to where sheep were imported relative to more distant counties. This is approximately

Figure 5: Effect of the European Sheep Import Bans on Sheep Scab Outbreaks



Note: This figure presents the event study plot for the effect of the ban on European sheep imports on the number of sheep scab outbreaks. The red, dashed line corresponds to the period where import bans on European sheep begin to be implemented. The blue rectangle corresponds to the period where sheep from the United States and Canada were subjected to port slaughter (December 31, 1895) and the period where universal port slaughter of all animals entering Britain was implemented (January 1, 1897). The outcome is the number of sheep scab outbreaks at the county-level. Standard errors are clustered at the county-level.

a 45% increase relative to the sample mean of 24 annual outbreaks. Column 2 presents the estimate when the sample is restricted to years between 1885 and 1895. This excludes years after the implementation of the port slaughter policies starting in 1896. The effect is slightly smaller but of similar magnitude. The remaining two columns address a potential concern that the increase in outbreaks was driven simply by counties having more domestic sheep.[8] These columns control for the number of domestic sheep using the data I digitized from the agricultural censuses. The estimated increase in outbreaks is slightly larger when controlling for the sheep population.

The Privy Council reported the number of sheep infected with sheep scab in addition to the number of farm outbreaks (see Figure A1). While I do not use the infections data as my main outcome because the Privy Council cautioned that there was more misreporting in the total number of infected sheep relative to known outbreaks, this data makes it possible to

[8]Figure A6 panel (b) plots the total number of domestic sheep over time, which shows that the supply of sheep was indeed increasing after the import bans.

study the effect of the ban on the intensive margin. Table B1 presents the results for the effect of the import bans on domestic sheep scab infections. Columns 1-4 present the result on the effect of the bans on infection. Across various specifications, the bans lead to approximately 250 additional annual sheep scab infections. The estimates imply an approximately 60% increase in infections relative to the sample mean, which is a moderately larger effect relative to the 45% increase in total outbreaks. The final two columns present the results where the outcome is the infection rate. The estimates imply approximately 110 additional sheep scab infections per 100,000 domestic sheep.[9]

Table 1: Effect of the European Sheep Import Bans on Domestic Sheep Scab Outbreaks

	Dependent variable:			
	Farm Outbreaks			
	(1)	(2)	(3)	(4)
$post_t \times proximity_c$	11.200***	8.923***	12.206***	10.086***
	(3.769)	(3.299)	(3.926)	(3.363)
$sheep_{ct}$			0.028	0.036*
			(0.022)	(0.020)
Dep. Var. Mean	24.307	23.511	24.431	23.709
Observations	1,535	933	1,527	925
R^2	0.779	0.822	0.780	0.824
Sample	Full	Pre-Port Slaughter	Full	Pre-Port Slaughter

Note: This table presents the results for the effect of the import bans on domestic sheep scab infections by estimating equation (1). The outcome is the number of sheep scab outbreaks on farms. The full sample uses data from 1885-1902. The pre-port slaughter sample uses data from 1885-1895 which restricts to the period prior to the port slaughter on Canadian and US sheep on January 1, 1896. Columns 1 and 2 present the baseline results and columns 3 and 4 control for the number of sheep (in thousands). The data are at the county-year level and include all counties in England, Wales, and Scotland. Standard errors are clustered at the county-level. *** p<0.01, ** p<0.05, * p<0.1.

The increase in outbreaks after the import bans is consistent with the descriptive pattern of sheep scab infections among imported animals presented in Figure 3. In years prior to the import bans very few imported sheep were infected with sheep scab. The ban on European imports caused British consumers to purchase sheep from the Americas that had

[9]In addition, Figure B4 provides the event study results for the effect on the sheep scab infection rate. The dynamics are similar to the main event study focusing on sheep scab outbreaks (Figure 5).

high prevalence of sheep scab. At the time of the bans, Canadian and American sheep were not restricted to port slaughter upon arrival in Britain. If infected sheep were not properly inspected at the port of entry, they may have been transported inland, where they could have spread the disease to domestic sheep. There is anecdotal evidence from contemporary agricultural newspapers discussing this issue. When summarizing the daily livestock market in London on October 4, 1895, the *Livestock Journal* wrote, "Foreign sheep in the Metropolitan Market comprised 3,790 from Canada and 1,260 from the United States... a large number of them were purchased as stores and sent broadcast into the country, where they may infect our native flocks with scab." Overall, these results highlight how imports bans can lead to trade diversion that can actually make health externalities from trade worse.

It is worth emphasizing that while the import ban led to an increase in domestic sheep scab infection, there was no increase in foot-and-mouth disease after the restrictions. The import bans were motivated by foot-and-mouth disease infection among imported sheep and the fear that this could spread to domestic sheep and cattle. Figure A8 panel (a) shows that before and after the ban, total foot-and-mouth infections among domestic livestock was nearly zero. Therefore, while the ban led to trade substitution that increased domestic sheep scab infection, it successfully kept foot-and-mouth out of Britain. The model portion of the paper in Section 7 will assess the relative welfare consequences between higher sheep scab or higher foot-and-mouth disease infection.

The remainder of the section presents several robustness checks. The first set of robustness checks relates to the fact that both Liverpool and London received a significant number of imported sheep from the Americas after the import ban. Table B2 presents the results with two alternative treatment definitions. Columns 1 and 4 show the effects on outbreaks and infections using the main treatment definition where $proximity_c$ is an indicator for whether the county is below median distance to either Liverpool or London. Columns 2 and 5 show the results where $proximity_c$ is an indicator for whether the county is below median distance to Liverpool specifically. Columns 3 and 6 show the results where treatment is an analogous indicator for distance to London. The results suggest the import bans led to an increase in both sheep scab outbreaks and infections across all specifications using these alternative treatment definitions.

Finally, Table B3 presents the results where treatment is defined as continuous distance instead of an indicator based on proximity. Across specifications using distance to Liverpool, London, or the nearer of the two, counties farther from the main ports receiving imported sheep experienced fewer sheep scab outbreaks and infections after the bans. This is consistent with

5.2 Effects of Less Restrictive Trade Policies

This section analyzes the health effects of a less strict trade restriction that British officials chose to adopt during the period. Before the Privy Council banned animals from an exporting country, it would often first require the animals be slaughtered at the port of entry. This compromise policy allowed animals to still be imported and ultimately consumed by British consumers while also reducing the disease threat by prohibiting imported animals from being transported inland. This section will analyze two key episodes where port slaughter was implemented on sheep imports.

The first major restriction on sheep imports into Britain occurred in 1877 when the Privy Council required sheep from several European countries to be slaughtered at the port of entry. These restrictions were enacted after 39 imported cattle examined at ports were found to be infected by rinderpest. The Privy Council responded swiftly and proactively to prevent a wider outbreak of rinderpest similar to the Cattle Plague of 1865. The Privy Council required imported sheep from five European countries – Belgium, France, Germany, the Netherlands, and Russia – to be slaughtered at the port of entry.

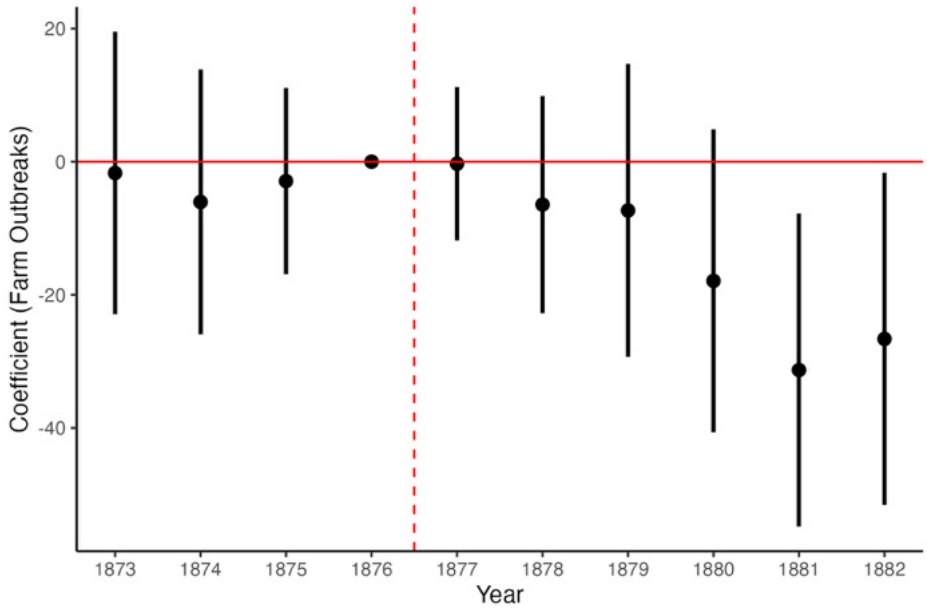
To analyze how this early policy of port slaughter affected disease transmission, I will follow a similar empirical strategy to the one used to analyze the import bans. Specifically, I will use an event study approach that compares sheep scab outbreaks in counties closer to the ports where sheep subjected to port slaughter were primarily imported to more distant counties. Figure B5 provides some descriptive information on the sheep trade just prior to the port slaughter policy to help motivate the empirical strategy. Panel (a) shows that in the year prior to the trade restrictions most of the imported sheep were coming from countries that would be subjected to port slaughter. Denmark was the only country with a significant number of imports that was not subsequently subjected to port slaughter. Panel (b) displays the exact ports within Britain that received sheep from the countries that would face the trade restrictions. The graph shows that the vast majority of the sheep were imported into London. Most of the remaining sheep were imported into Harwich on the southeastern coast of England. The fact that most animals were imported into the southeastern part of Britain likely reflects that during this early period Britain's trading partners were mostly European countries.

Given this information on the trade patterns, to assess the effect of the 1877 port slaughter policy on sheep scab outbreaks I estimate equation (1) with one main modification. $proximity_c$ is whether the county is below the minimum median distance to either London or Harwich, the two main ports where sheep were imported.

Figure 6 provides the event study results from estimating equation (1) where $proximity_c$ is interacted with year fixed effects. In years prior to port slaughter, disease dynamics are

similar in counties near the main ports where sheep were imported and counties further away. In subsequent years, sheep scab outbreaks begin to decline in nearby counties. This suggests that port slaughter was effective at reducing the spread of disease to domestic animals. There are two likely reasons why port slaughter was effective at reducing disease transmission, in contrast to the subsequent episode of import bans studied previously. First, port slaughter prohibited foreign animals from being transported inland and transmitting disease to domestic livestock. Second, there was little substitution to new trade partners after the 1877 port slaughter policy that may have had higher prevalence of sheep scab in their flocks. Figure 1 panel (b) shows that Germany and the Netherlands, the two largest trade partners, account for approximately the same share of total imports before and after port slaughter was implemented. Figure 3 panel (a) shows that the number of imported sheep with sheep scab declined in the years after the 1877 port slaughter policy, in contrast to the later episode of import bans.

Figure 6: Effect of the 1877 Port Slaughter Policy on Sheep Scab Outbreaks



Note: This figure presents the event study plot for the effect of the 1877 policy mandating port slaughter of sheep from five European countries. The outcome is the number of sheep scab outbreaks at the county-level. The red, dashed line corresponds to when port slaughter was implemented. Standard errors are clustered at the county-level.

The second episode of port slaughter policies, which we discussed in the previous section, occurred after the series of import bans on European sheep. Motivated by the large increase in sheep scab infections among imported sheep in the early 1890s from the Americas, the Privy Council subjected sheep from the United States and Canada to port slaughter on

December 31, 1895. Mandatory port slaughter was then extended on January 1, 1897 to all animals – regardless of animal type or exporting country – being imported into Britain.

The event study results in Figure 5 on the effect of the import bans on sheep scab outbreaks provides evidence that these subsequent port slaughter policies were also effective at reducing disease transmission. Outbreaks in counties closer to where sheep were imported increase until 1897 and then decline in subsequent years. The decline in outbreaks coincides with the period, marked by the blue rectangle, when the Privy Council implemented mandatory port slaughter.

This finding aligns with the anecdotal impressions of contemporary British officials. The 1898 Board of Agriculture Annual Report states, "The Diseases of Animals Act, 1896, rendered necessary the slaughter at the port of landing of all foreign animals conveyed to this country, and brought about a very material change in the position with regard to the possible eradication of sheep-scab." Figure 7 provides the full excerpt. The report discusses how physically examining animals at the port of entry alone could not prevent imported animals from spreading disease. The veterinarians conducting the examinations might miss infected animals. Or animals might be in an early stage of infection and not display obvious symptoms. The findings from the event study provide evidence corroborating the impressions of the British officials that port slaughter was effective at preventing sheep scab from spreading from foreign to domestic sheep.

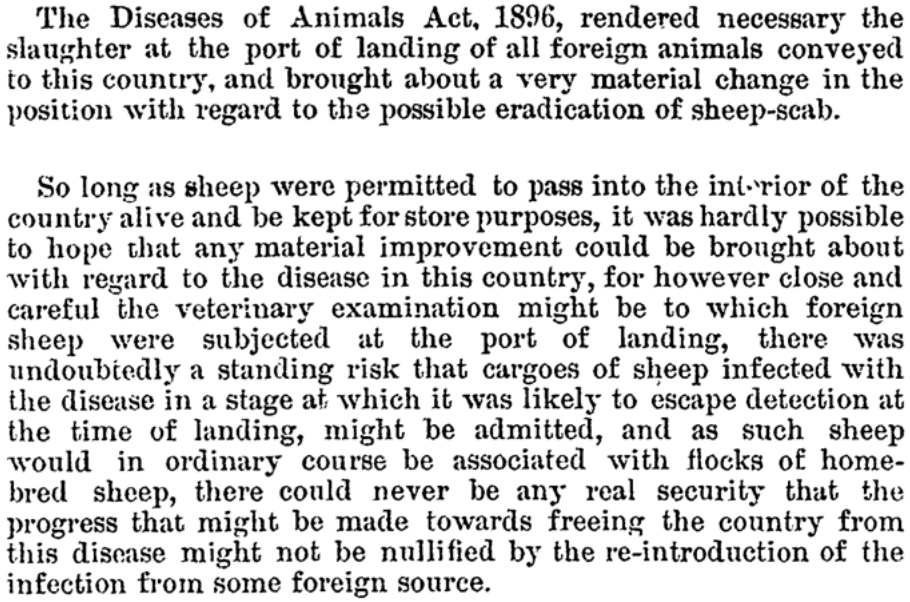
6 The Economic Effects of the Import Bans

This section examines the economic effects of the import ban on German sheep in 1889 as well as the earlier port slaughter policy in 1877. Understanding the economic effects of the trade restrictions explores another dimension of how the policies impacted overall welfare. The first part examines the effects of the trade restrictions on domestic meat prices. Given the significant increase in sheep scab, the second part examines whether the ban on European imports affected domestic wool production.

6.1 Effects on Meat Prices

To assess the economic effects of the trade restrictions, I digitize data from historical newspapers on meat prices around the two key episodes in 1877 and 1889. The primary focus will be on meat prices in London since local newspapers kept remarkably detailed data on the two weekly livestock markets in the city. Figure A5 provides an example of the data reported in *The Times*. I digitize information on the number of livestock at the market as well as

Figure 7: Excerpt of British Officials Discussing Effects of the 1896 Port Slaughter Law



The Diseases of Animals Act, 1896, rendered necessary the slaughter at the port of landing of all foreign animals conveyed to this country, and brought about a very material change in the position with regard to the possible eradication of sheep-scab.

So long as sheep were permitted to pass into the interior of the country alive and be kept for store purposes, it was hardly possible to hope that any material improvement could be brought about with regard to the disease in this country, for however close and careful the veterinary examination might be to which foreign sheep were subjected at the port of landing, there was undoubtedly a standing risk that cargoes of sheep infected with the disease in a stage at which it was likely to escape detection at the time of landing, might be admitted, and as such sheep would in ordinary course be associated with flocks of home-bred sheep, there could never be any real security that the progress that might be made towards freeing the country from this disease might not be nullified by the re-introduction of the infection from some foreign source.

Note: This figure contains an excerpt from the Board of Agriculture annual reports that provides the perspective of contemporary British officials which suggests the policy passed in 1896 requiring mandatory port slaughter for all imported animals was important in addressing sheep scab infection. This excerpt is from: *Board of Agriculture, Annual Reports of Proceedings Under the Diseases of Animals Acts, The Markets and Fairs (Weighing of Cattle) Acts, For the Year 1898*, pg. 36.

prices at a monthly frequency for a three-year window around each trade restriction. For the 1889 trade restriction, the newspaper also consistently provides short summaries of the market in Liverpool. I digitize this data on prices in Liverpool to supplement the analysis for London.

London had two livestock markets a week on Tuesdays and Thursdays. In 1855, the city opened the Metropolitan Cattle Market located in Islington which had extensive facilities to house and slaughter animals. In response to the animal disease outbreaks of the 1860s, London created a second market specifically for the purpose of slaughtering imported animals. The Foreign Cattle Market opened in 1872, and was located along the southern bank of the Thames in Deptford. British officials hoped that keeping foreign and domestic livestock separate would help prevent the spread diseases (Perren, 1978). The empirical analysis will focus on the price of domestic livestock at the Metropolitan Cattle Market because *The Times* reported prices for domestic animals consistently over the entire sample period. Even though the domestic and foreign livestock markets were segmented, we would expect the prices of domestic livestock to respond to changes in trade policy.

To examine the effects on prices, I employ a difference-in-differences empirical strategy

comparing the price of sheep meat (mutton) to the price of cattle meat (beef), before and after the trade restrictions on sheep imports. Specifically, I estimate the following equation separately for each trade restriction episode:

$$price_{mt} = \alpha_o + \alpha_1 mutton_m + \alpha_2 post_t + \beta mutton_m \times post_t + \epsilon_{mt} \tag{2}$$

Where $price_{mt}$ is the price of the type of meat m at time t. $mutton_m$ is an indicator equal to one when the meat is mutton and zero if it is beef. $post_t$ is an indicator equal to one in months after the implementation of the trade restriction, and zero otherwise. The Veterinary Department annual reports contain information on the exact dates that the trade restrictions were implemented. The port slaughter of sheep was implemented on January 18, 1877 and the ban on German sheep imports occurred on March 22, 1889. β is the coefficient of interest which captures the change in the price of mutton relative to the price of beef before and after the implementation of the respective trade restriction.

I choose to estimate the effects of the trade restrictions by comparing mutton versus beef prices for several reasons. First, to the best of my knowledge systematic data on meat prices across British cities does not exist during the period. Local newspapers, such as *The Times*, would sometimes report information about local livestock markets. However, the way in which the data was reported often varied across locations making it difficult to construct a comparable panel of prices across cities. This prevents using geographic variation, such as the location where animals were imported, to estimate effects on prices. However, even if such a panel existed, using geographic variation would potentially lead to biased estimates because internal movements of livestock across regions within Britain would likely equalize prices across locations. Comparing meat types does not suffer from this issue. If beef and mutton are substitutes, this may attenuate the effect as consumers increase purchases of beef in response to the restricted supply of sheep. This would imply the estimated effect is a lower bound for the true change in price.

Before turning to regression results, Figure 8 presents the descriptive trends in mutton and beef prices around each of the two trade restrictions. Examining the trends in meat prices prior to the implementation of the restrictions can help assess potential violations in the parallel trends assumptions. Panel (a) displays the prices around the 1889 ban on German sheep imports. Beef and mutton prices are following a similar increasing trend in the period prior to the ban on German sheep imports. After the ban, the prices begin to diverge as mutton prices increase relative to beef. This provides descriptive evidence that the import ban led to higher meat prices. Panel (b) displays the meat prices around the 1877 policy mandating port slaughter on the five main European exporting countries. Mutton and beef prices are roughly flat and trending similarly prior to port slaughter. In contrast

to the import ban, there is little change in the relative prices after the port slaughter policy was implemented.

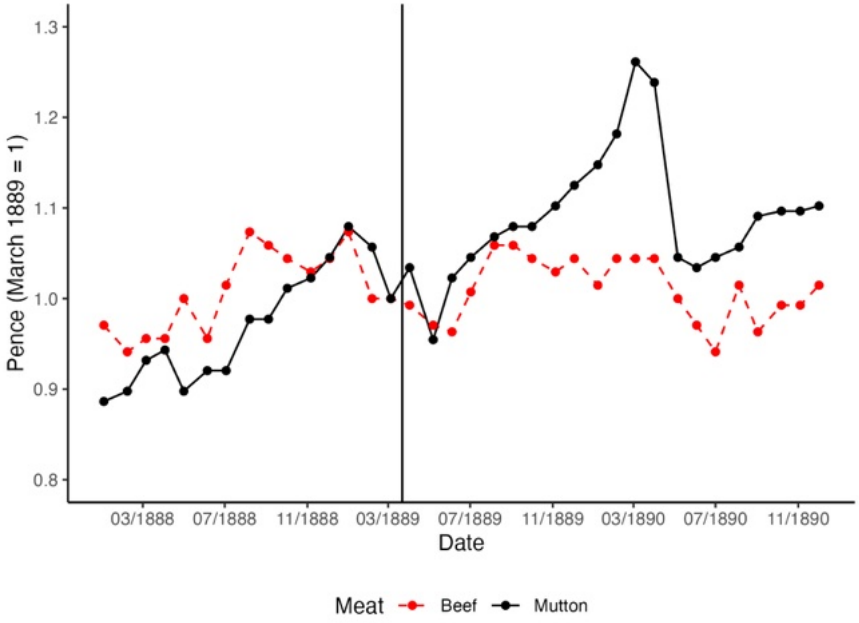
Table 2 presents the results of estimating equation (2) for the two trade restriction events where the outcome is the price per eight pounds of meat in either levels or logs. The first four columns focus on the effects of the import ban. The coefficient on $mutton_m \times post_t$ in column 2 implies that the price of mutton in London increased approximately 11% relative to the price of beef after the import ban. Column 4 shows that mutton prices also increased in Liverpool, although by a smaller magnitude of approximately 6%. Overall, the results for London and Liverpool suggest that the ban on German sheep imports led to higher meat prices for domestic consumers in Britain. In contrast, column 6 shows that there was no change in the price of mutton relative to beef in London after the implementation of the port slaughter policy in 1877. The coefficient is not statistically significant and small in magnitude. The odd columns of Table 2 present robustness where the outcome is the meat price in levels instead of logs. The results are consistent across the various specifications using this modified functional form.

The large increase in mutton prices after the import bans is consistent with the changes in import patterns presented in Figure 1 panel (a). In the years after the import bans there was a large reduction in sheep imported to Britain. However, if British farmers responded to the reduction in foreign supply by sending more of their own animals to market this would overstate the total change in mutton supply. Figure B7 addresses this point by plotting the number of sheep sold at the London livestock market by origin status. The number of foreign sheep sold at market declined dramatically from approximately 800,000 before the ban to 10,000 in 1893. The number of domestic sheep sent to the London market increased modestly over the same period from approximately 700,000 before the ban to 870,000 in 1893. This implies that on net the supply of sheep declined significantly after the ban which is consistent with the estimated increase in mutton prices in Table 2.

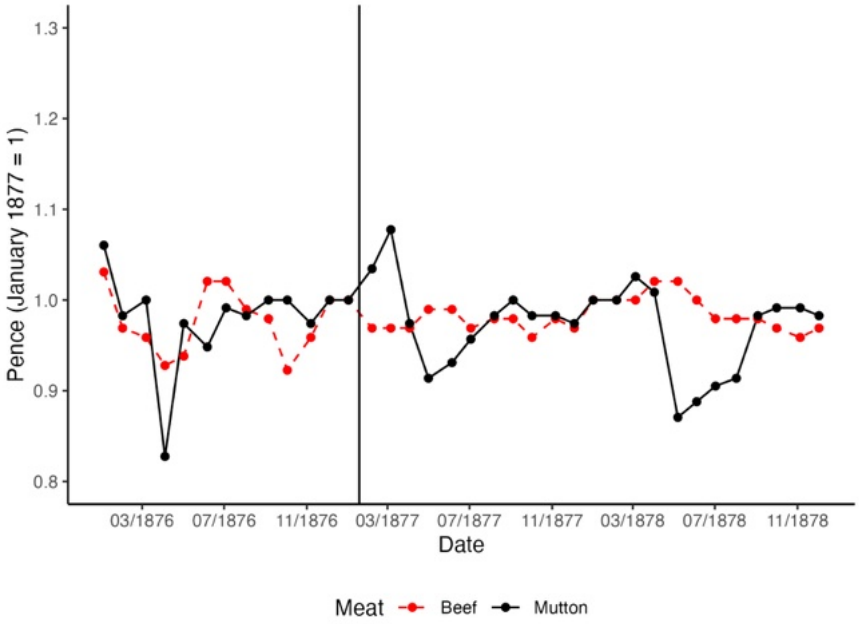
In contrast, Figure 1 panel (a) shows that after the port slaughter policy was adopted in 1877 there was a much smaller reduction in the number of imported sheep. The small change in supply is consistent with the null effect on meat prices in Table 2. Overall, this illustrates a key difference between the two policies. The import bans disrupted the supply of imported meat as Britain found new trading partners. This led to higher meat prices as supply declined. Port slaughter did not disrupt the existing trade relationships as the European countries subjected to the policy were still able to import animals if they were not transported inland and incorporated into the domestic flock.

Figure 8: Comparison of Beef and Mutton Prices in London Around the Trade Restrictions

(a) Meat Prices Around the 1889 Ban on German Sheep Imports



(b) Meat Prices Around the 1877 Port Slaughter Restrictions



Note: This figure compares the price of beef and mutton at the Metropolitan Cattle Market in London around the two trade restriction episodes. Panel (a) shows the prices around the ban on German sheep imports that was implemented on March 22, 1889. The black, vertical line indicates the day the restriction was implemented. Panel (b) shows the prices around the mandatory port slaughter of sheep that was implemented on January 18, 1877. Similarly, the black, vertical line displays the date of implementation. The prices are collected monthly from *The Times*. The black, solid line displays the mutton price and the red, dashed line displays the beef price. Prices are normalized so the last month prior to the restriction equals one.

Table 2: The Effects of Trade Restrictions on Meat Prices

	Dependent variable:					
	Pence	log(Pence)	Pence	log(Pence)	Pence	log(Pence)
	(1)	(2)	(3)	(4)	(5)	(6)
$mutton_m$	11.289***	0.220***	9.378***	0.177***	12.538***	0.180***
	(1.128)	(0.019)	(1.060)	(0.020)	(1.174)	(0.016)
$post_t$	0.089	0.002	−0.965	−0.020	0.280	0.005
	(1.044)	(0.018)	(0.981)	(0.018)	(1.039)	(0.015)
$mutton_m \times post_t$	6.933***	0.114***	3.702***	0.066**	−0.857	−0.012
	(1.476)	(0.025)	(1.387)	(0.026)	(1.469)	(0.021)
Constant	45.689***	3.821***	48.267***	3.876***	63.256***	4.147***
	(0.797)	(0.014)	(0.749)	(0.014)	(0.830)	(0.012)
Dep. Var. Mean	53.407	3.965	53.472	3.972	69.431	4.236
Observations	72	72	72	72	72	72
R^2	0.878	0.892	0.812	0.815	0.810	0.818
City	London	London	Liverpool	Liverpool	London	London
Policy	Ban	Ban	Ban	Ban	Port Slaughter	Port Slaughter

Note: This table presents the results for the effects of the trade restrictions on meat prices by estimating equation (2). Columns 1 to 4 present the results for the effect of the ban on German imports implemented on March 22, 1889. Columns 1 and 2 present the effect of the ban on meat prices in London. Columns 3 and 4 present the effect of the ban on meat prices in Liverpool. Columns 5 and 6 present the results for the effect of the port slaughter policy implemented on January 18, 1877 on meat prices in London. The dependent variable in odd columns is the price in pence per eight pounds of meat in levels. The dependent variable in even columns is the price in pence per eight pounds of meat in logs. The prices are collected monthly from *The Times* (see Figure A5). *** p<0.01, ** p<0.05, * p<0.1.

6.2 Effects on Wool Production

This section explores a final way in which the trade restrictions potentially had downstream economic effects. Sheep served two primary purposes by providing meat and wool that was turned into clothing. Given that sheep scab was a skin disease, it directly affected the quality and quantity of wool that a sheep produced. The analysis in Section 5 showed that the import ban on European sheep led to more sheep scab among domestic sheep. This may have had negative effects on domestic wool production.

However, analyzing the effects on the wool industry is difficult because data on wool production is not readily available to the best of my knowledge. For instance, the annual agricultural censuses in Britain collected information on the number of livestock, including sheep, but did not collect information on wool yields. While data on wool production is not available, data on wool exports exist and Britain exported a significant amount of wool during the period given the high quality wool that its sheep produced. If exports respond to changes in domestic supply, this data can proxy for changes in overall wool production. I collect data on wool exports from 1885–1895, covering the years leading up to the import bans and extending to just before the mandatory port slaughter of American and Canadian sheep in 1896.[10] The data contain exports at 23 ports across England, Wales, Scotland, and Ireland.

To assess the effect of the import bans on wool production, I compare wool exports from ports where sheep were imported into Britain to ports that did not receive a significant number of sheep imports. Section 5 showed that counties near the ports where sheep were imported (London and Liverpool) had more sheep scab outbreaks after the import bans. If sheep farmers were more likely to export wool at ports near their farms, then we might expect exports to decline at ports near counties where sheep scab outbreaks were worse after the import bans. Specifically, I estimate the following equation:

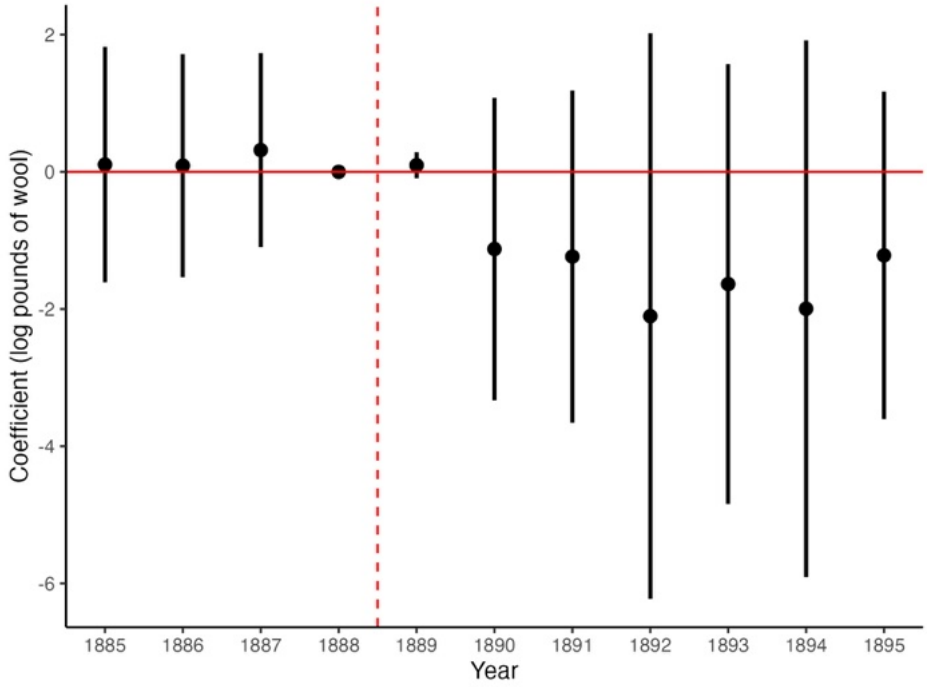
$$\log(wool_{pt} + 1) = \alpha + \beta \mathbb{1}\{t > 1888\}_t \times treat_p + \alpha_t + \alpha_p + \epsilon_{pt} \tag{3}$$

Where $wool_{pt}$ is either the weight or value of wool exported from port p in year t. $\mathbb{1}\{t > 1888\}_t$ is an indicator equal to one for years after 1888 which corresponds to when the import bans on European sheep start to be enacted. $treat_p$ is an indicator equal to one for the ports of London and Liverpool which are the two main ports where sheep were imported into Britain (see Figure 2). α_t and α_p are year and port fixed effects, respectively.

Figure 9 presents the event study estimates from equation 3 where the post treatment indicator is replaced with year fixed effects. Before the import bans, the coefficients are

[10] Data are taken from various editions of the *Annual Statement of Trade of the United Kingdom*.

Figure 9: Effect of the European Sheep Import Bans on Wool Exports (Weight in Pounds)



Note: This figure presents the event study plot for the effect of the European sheep import bans on wool exports. The red, dashed line corresponds to the period where import bans on European sheep begin to be implemented. The outcome is the log weight (in pounds) of wool exports at the port-level. Standard errors are clustered at the port-level.

close to zero suggesting wool exports at London and Liverpool were not trending differently than other ports in Britain. While the estimates are noisy given there are only two treated units, the event study suggests wool exports declined in the years after the import bans. The event study in Figure B8 shows a similar pattern when the value of wool exports is used as the outcome variable instead of the weight. Although the event studies are noisy, Table B4 shows that the difference-in-differences results from estimating equation 3 are statistically significant. There are caveats with this analysis since we do not directly observe wool production and there are only two treated units. Yet the results are consistent with the import bans on European sheep reducing wool production as they increased sheep scab among domestic sheep.

7 Model and Welfare Analysis

This section presents a simple model that explores the interactions between domestic animal production, animal disease transmission, and international trade. The primary objectives of

the model are to highlight how health externalities can reduce the gains from trade and to perform welfare assessments of different trade scenarios that resemble the trade restrictions implemented by British officials. The first two sections present the model and discuss the analytical steady state. The last section calibrates the model and uses it to discuss the welfare effects of different trade policy scenarios in the presence of health externalities.

7.1 Set-Up

Household Preferences, Endowments, and Problem: In the domestic country (Britain) there is a representative household that has Cobb-Douglas preferences over four goods: beef from cattle (b_t), mutton from sheep (m_t), wool from sheep (w_t), and an additional good (g_t) that captures other household consumption.

$$u(b_t, m_t, w_t, g_t) = b_t^{\alpha_1} m_t^{\alpha_2} w_t^{\alpha_3} g_t^{\alpha_4} \tag{4}$$

Where $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1$. Modeling household consumption in this manner makes it possible to capture the main ways in which animal diseases affected domestic consumption.

The household is endowed with a unit of labor each period $N_t = 1$, L units of land, and an initial amount of sheep and cattle given by the following equations:

$$s_0 = h_{s,0} + i_{s,1,0} + i_{s,2,0} + i_{s,3,0} \tag{5}$$

$$c_0 = h_{c,0} + i_{c,2,0} \tag{6}$$

There are two potential diseases that the livestock can contract: sheep scab (disease 1) and either foot-and-mouth or rinderpest (disease 2).[11] A key feature of the context that is important for the welfare analysis is that the first disease (sheep scab) only affects sheep whereas the second disease (either foot-and-mouth or rinderpest) can transmit between species. The sheep are split into four categories based on their health status. The number of healthy sheep at time zero is $h_{s,0}$, the number of sheep infected with the first disease (sheep scab) is $i_{s,1,0}$, the number infected with the second disease is $i_{s,2,0}$, and the number infected with both diseases is $i_{s,3,0}$. The endowment of cattle is split into only two categories since cattle do not contract sheep scab. Therefore, at time zero there are $h_{c,0}$ healthy cattle and $i_{c,2,0}$ infected with the second disease.

[11] Instead of treating the second disease as either foot-and-mouth or rinderpest, a third could be introduced to form a three-disease model. However, the results would be similar to the two-disease case comparing sheep scab to either disease, since the key tradeoff is between a sheep-specific disease and one that can spread across species and affect domestic beef production.

The household maximizes utility in equation (4) subject to its income given by the equation below. The household has three sources of income: wage income, income from selling adult sheep for slaughter, and income from selling adult cattle for slaughter.

$$I = p_{nt}N_t + p_{st}s_t + p_{ct}c_t \tag{7}$$

Production Technologies and Firm Problems: there are three technologies that determine the level of the outside good g_t, sheep s_t, and cattle c_t each period, along with three additional technologies for how sheep and cattle are converted into wool w_t, mutton m_t, and beef b_t.

First, a firm hires the household to produce the outside good according to the production function $g_t^d = A_t N_t$, where A_t measures productivity. Growth in A_t over time could capture the fact that Britain was industrializing during the period and help motivate incentives to import meat products. We treat g_t as the numeraire, so the price of the good is $p_{gt} = 1$. The firm's profit maximization problem implies the wages from household labor are $p_{nt} = A_t$.

Second, at the beginning of the period the livestock give birth to the young flock of animals for next period. The number of livestock evolves mechanically over time according to Cobb-Douglas laws of motion with two inputs: the amount of available land L and the number of livestock that are able to reproduce. The laws of motion for sheep and cattle are given by:

$$s_{t+1} = \varphi(\lambda L)^{\sigma}(h_{s,t} + \theta_1 i_{s,1,t} + \theta_2 i_{s,2,t} + \theta_3 i_{s,3,t})^{1-\sigma} \tag{8}$$

$$c_{t+1} = \varphi((1-\lambda) L)^{\sigma}(h_{c,t} + \theta_2 i_{c,2,t})^{1-\sigma} \tag{9}$$

The term in parentheses represents the number of animals that can reproduce. All health animals can reproduce, however, only shares θ_1, θ_2, θ_3 of the animals infected with disease 1, disease 2, and both diseases can reproduce. This is the first way in which the effect of disease on domestic agricultural production is modeled. It captures important features of the context since some diseases were fatal or farmers immediately slaughtered them to prevent further disease spread. Furthermore, many diseases – such as foot-and-mouth and sheep scab – had direct effects on animal fertility. We assume $\sigma < 1$, which implies diminishing returns in the number of livestock given fixed land. We assume that a fraction λ of total land is devoted to sheep and the remaining share $1 - \lambda$ is devoted to cattle. This provides a simple way to account for differences in the number of sheep and cattle observed in the data. φ captures agricultural productivity.

Among the new flock of livestock, the number of "young" healthy livestock is given by the following equations:

$$h_{s,t+1} = s_{t+1} - i_{s,1,t+1} - i_{s,2,t+1} - i_{s,3,t+1} \tag{10}$$

$$h_{c,t+1} = c_{t+1} - i_{c,2,t+1} \tag{11}$$

The number of infected "young" livestock will depend on the number of infected imported animals, and will be discussed in more detail later.

The second way in which disease affects domestic agricultural production is by reducing the amount of meat and wool that livestock produce. We assume all "old" livestock are consumed each period. The following equations give the amount of each agricultural good that is produced from the livestock:

$$w_t = h_{s,t} + \delta_1^w i_{s,1,t} + \delta_2^w i_{s,2,t} + \delta_3^w i_{s,3,t} \tag{12}$$

$$m_t = h_{s,t} + \delta_1^m i_{s,1,t} + \delta_2^m i_{s,2,t} + \delta_3^m i_{s,3,t} \tag{13}$$

$$b_t = h_{c,t} + \delta_2^b i_{c,2,t} \tag{14}$$

Healthy sheep and cattle each produce a unit of wool, mutton, and beef. However, the infected animals produce a discounted amount of each good that is captured by the δ terms. The discount that a particular disease causes is good-specific. This captures the idea that sheep scab had significant negative effects on wool production and more modest effects on mutton output (and vice versa for foot-and-mouth). A second important feature is that only the second disease negatively affects beef production.

To pin down prices, two additional representative firms convert livestock into each of the goods. A firm purchases sheep from the household and produces wool and mutton according to the technologies. Similarly, a firm purchases cattle from the household and produces beef.

$$\pi = p_{mt} m_t + p_{wt} w_t - p_{st} s_t \tag{15}$$

$$\pi = p_{bt} m_t - p_{ct} c_t \tag{16}$$

Autarky: To introduce trade in the model and to compare different policy scenarios, it is useful to first specify the equilibrium of the model in autarky when there is no domestic

disease ($i_{s,1,0}, i_{s,2,0}, i_{s,3,0}, i_{c,2,0} = 0$). This will be benchmark equilibrium when assessing the welfare effects of trade policies.

The steady-state level of cattle, sheep, and the price of sheep in autarky is given by the following equations. Appendix C.1.1 presents additional details on the derivation.

$$c^a = \varphi^{\frac{1}{\sigma}}(1-\lambda)L, \qquad s^a = \varphi^{\frac{1}{\sigma}}\lambda L, \qquad p_s^a = \frac{(\alpha_2+\alpha_3)AN}{\alpha_4\,\varphi^{\frac{1}{\sigma}}\lambda L} \tag{17}$$

International Trade: In the version of the model with trade, the domestic country has the ability to trade with two exporting countries E (Europe) and A (the Americas). Allowing for trade with two countries makes it possible to examine the trade substitution dynamics after the import ban discussed in the empirical sections.

We assume that both countries are able to elastically supply as many sheep as domestic consumers want at prices p_s^E and p_s^A. Crucially, assume that the price of sheep in these countries is lower than the autarky price in the domestic country: $p_s^E \leq p_s^A < p_s^a$. This assumption ensures that the domestic country specializes in and exports the outside good and the other countries will export sheep. The domestic country will import s^f sheep from whichever country has the lowest sheep price and that price will prevail as the price in both countries p_s^T.

Note that for simplicity Britain cannot import cattle as well. While Britain was importing cattle as well as sheep (see Figure A7), because of various disease outbreaks cattle imports were banned for many countries prior to trade restrictions on sheep. So trade in sheep is the most salient risk when considering health externalities from trade during the period.

Disease: To complete the model we need to specify disease dynamics that determine the number of young infected livestock. Assume that shares r_1^f and r_2^f of the imported foreign sheep are infected with diseases 1 and 2, respectively. Then the number of "young" sheep infected with each disease is given by:

$$i_{s,1,t+1} = \left(\frac{r_1^f s_t^f + i_{s,1,t} + i_{s,3,t}}{s_t^f + s_t}\right)\beta_1 s_{t+1} - i_{s,3,t+1} \tag{18}$$

$$i_{s,2,t+1} = \left(\frac{r_2^f s_t^f + i_{c,2,t} + i_{s,2,t} + i_{s,3,t}}{s_t^f + c_t + s_t}\right)\beta_2 s_{t+1} - i_{3,t+1} \tag{19}$$

Before slaughter, the old animals interact with the "young" sheep (s_{t+1}) and potentially infect them. Following the epidemiology literature, I assume random interactions between the young and old, so the probability of coming into contact with an infected animal is simply the share of old animals that are infected. The terms in brackets represent these shares. Since sheep scab could only transmit between sheep, the term in bracket in equation

(18) only contains sheep. However, since the second disease (foot-and-mouth or rinderpest) can transmit between species, the term in brackets in equation (19) contains both sheep and cattle. The terms β_1 and β_2 capture the diseases virulance, and represent the probability of infection conditional on contact with an infected animal. For accounting simplicity, it is helpful that $i_{s,1,t+1}$ and $i_{s,2,t+1}$ represent the number of young sheep infected only with a single disease, therefore, I subtract off $i_{s,3,t+1}$ which is the number of young sheep infected with both. Assuming that disease dynamics for the two diseases are independent, the following equation gives the total young sheep infected with both.

$$i_{s,3,t+1} = \left(\frac{r_1^f s_t^f + i_{s,1,t} + i_{s,3,t}}{s_t^f + s_t}\right)\left(\frac{r_2^f s_t^f + i_{c,2,t} + i_{s,2,t} + i_{s,3,t}}{s_t^f + c_t + s_t}\right)\beta_1\beta_2 s_{t+1} \tag{20}$$

Finally, the number young cattle infected with the second disease is given by the equation below. The equation takes the same form as equation (19) since there is potential interspecies transmission, however, there is no comorbidity term since cattle could not contract sheep scab.

$$i_{c,2,t+1} = \left(\frac{r_2^f s_t^f + i_{c,2,t} + i_{s,2,t} + i_{s,3,t}}{s_t^f + c_t + s_t}\right)\beta_2 c_{t+1} \tag{21}$$

Market Clearing: To complete the model, we need to specify the market clearing and trade balance conditions. The market clearing for each of the four goods is presented in the equation below. Total wool and mutton consumption is equal to the amount produced from the domestic and imported sheep ($s_t + s_t^f$) via equations (12, 13). Total beef consumption equals the amount produced from domestic cattle since trade is only allowed in sheep. Lastly, total outside good consumption equals the amount produced from household labor, minus the amount that is traded with the exporting country in return for sheep. Trade balance implies that the value of the exported goods equals the value of the imported sheep: $p_{gt}g_t^f = p_{st}s_t^f$.

$$w_t = w_t^d + w_t^f, \quad m_t = m_t^d + m_t^f, \quad b_t = b_t^d, \quad g_t = g_t^d - g_t^f \tag{22}$$

7.2 Steady State

This section discusses the equilibrium of the model. Appendix C.1.3 provides additional details on deriving the steady state. When making the restriction that $\beta_1 = \beta_2 = 1$, it is possible to solve for the steady state analytically. The steady state level of domestic sheep and cattle is given by:

$$s^* = \varphi^{\frac{1}{\sigma}} \lambda L \Bigg(1 - \underbrace{r_1^f(1-\theta_1)}_{\text{disease 1 penalty}} - \underbrace{r_2^f(1-\theta_2)}_{\text{disease 2 penalty}} + \underbrace{r_1^f r_2^f(1-\theta_1-\theta_2+\theta_3)}_{\text{comorbidity term}}\Bigg)^{\frac{1-\sigma}{\sigma}} \tag{23}$$

$$c^* = \varphi^{\frac{1}{\sigma}} (1-\lambda) L \Bigg(1 - \underbrace{r_2^f(1-\theta_2)}_{\text{disease 2 penalty}}\Bigg)^{\frac{1-\sigma}{\sigma}} \tag{24}$$

When no imported animals have disease ($r_1^f = r_2^f = 0$), the steady-state livestock corresponds to the level in autarky discussed above. However, when imported animals are infected, this reduces the steady-state number of livestock due to disease spreading from the foreign to domestic animals. For illustration, consider the penalty associated with disease 1. The steady-state livestock will be lower if the share of imported animals with the disease increases (r_1^f) and if the disease is particularly severe prohibiting reproduction (lower θ_1). Steady-state livestock will then depend on the relative prevalence of each disease among imported livestock as well as the relative severity. Disease makes households worse off by reducing the amount of livestock they can sell which reduces overall income for consumption.

Equations (25-27) present the steady state level of domestic wool, mutton, and beef output produced from domestic sheep and cattle. These equations highlight the second mechanism through which disease makes households worse off. Disease can reduce the amount of each good that is produced from infected sheep, and the penalty is worse if more sheep are imported with disease (higher r_1^f, r_2^f) or the impact of infection on production is more severe (lower δ's). This will increase the equilibrium price of each good, and reduce overall household consumption.

$$w_d^* = s^* \Big(1 - r_1^f\big(1-\delta_1^w\big) - r_2^f\big(1-\delta_2^w\big) + r_1^f r_2^f\big(1-\delta_1^w-\delta_2^w+\delta_3^w\big)\Big) \coloneqq s^* \Delta_w \tag{25}$$

$$m_d^* = s^* \Big(1 - r_1^f\big(1-\delta_s^m\big) - r_2^f\big(1-\delta_2^m\big) + r_1^f r_2^f\big(1-\delta_1^m-\delta_2^m+\delta_3^m\big)\Big) \coloneqq s^* \Delta_m \tag{26}$$

$$b_d^* = c^* \big(1 - r_2^f(1-\delta_2^b)\big) \coloneqq c^* \Delta_c \tag{27}$$

7.3 Welfare Assessment of Trade Policy Scenarios

This section uses the model to assess the welfare of various trade policy scenarios. The main use of the model will be to compare the import ban on European sheep in the late 1880s to

alternative trade policies that the British government could have chosen.

Figure B9 presents a diagram illustrating the various trade policy scenarios considered in the welfare analysis. Using values for parameters discussed in the calibration Table B5, I first calculate the steady state of the model in autarky using the analytical solution discussed in Appendix C.1. I then compare the autarky equilibrium to several counterfactual scenarios. The first is when the economy opens to trade, without any health externality. In this scenario, Britain can purchase sheep abroad at 80% the price in autarky. In the next counterfactual, Britain can still engage in trade at the lower price of sheep, yet the trade comes with disease risk. Specifically, three percent of sheep that are imported have sheep scab ($r_1^f = .03$). This scenario broadly captures the environment Britain was facing just before the ban on European sheep. Then there are two alternative paths that are considered after Britain started to detect sheep infected with foot-and-mouth arriving from Europe. First, resembling the policy it adopted, it could ban European sheep. This led to a large increase in sheep scab infection as Britain substituted toward sheep from the Americas, but the ban successfully kept foot-and-mouth out of Britain. Overall, this is modelled as an increase in the sheep scab infection rate to $r_1^f = .08$ and no increase in foot-and-mouth infection $r_2^f = 0$. Second, Britain could have continued to allow sheep from Europe. This would likely have resulted in lower sheep scab infection similar to the pre-existing equilibrium ($r_1^f = .03$) but higher foot-and-mouth infection since the disease was spreading in Europe. I set the amount of foot-and-mouth disease in imported sheep to be 2% ($r_2^f = .02$) which is broadly consistent with past outbreaks of the disease among imported sheep.

Table 3 presents key parameter values used in the model calibration.[12] The household spends 15% of total income on beef, mutton, and wool ($\alpha_1, \alpha_2, \alpha_3 = .15$). This is broadly consistent with work by economic historians studying household expenditure in 1880 and 1900 (Perren, 1978). Britain can import sheep at 80% the price in autarky which broadly aligns with the price of foreign meat in Harley (2008). The next key parameters relate to the ability for livestock to reproduce if infected. I choose these parameters based on data collected from the Veterinary Department annual reports on the mortality rates of the different diseases. Overall, sheep scab and foot-and-mouth disease are not very fatal ($\theta_1 = .95$ and $\theta_2 = .97$, respectively). However, rinderpest is very fatal, so for the counterfactual in which it is the second disease I set $\theta_2 = .16$. The last important parameters relate to how much of each good is produced from animals infected with each disease. I assume sheep infected with sheep scab produce 60% of the wool of healthy sheep $\delta_1^w, \delta_3^w = .6$ (Rehbein et al., 2000). Lastly, I assume that cattle and sheep infected with foot-and-mouth disease produce 75% of the meat of healthy animals $\delta_2^b, \delta_2^m = .75$. Foot-and-mouth doesn't have

[12] Table B5 presents the extended list of values for all parameters in the model

significant effects on wool production and similarly sheep scab does not significantly affect meat production so I set $\delta_2^w, \delta_1^m = .9$.

Table 3: Key Parameter Choices for the Model Calibration

Parameter	Value	Source
$\alpha_1, \alpha_2, \alpha_3$	.15	Perren (1978)
p_s^T	$.8p_s^a$	Harley (2008)
θ_1	.95	Figure B11
θ_2	.97	Figure B11
θ_3	.95	Figure B11
δ_2^b	.75	Young et al. (2013)
δ_1^m	.9	Young et al. (2013)
δ_2^m	.75	Young et al. (2013)
δ_3^m	.75	Young et al. (2013)
δ_1^w	.6	Rehbein et al. (2000)
δ_2^w	.9	Young et al. (2013)
δ_3^w	.6	Rehbein et al. (2000)

Note: This table presents some of the key parameters used in the model calibration for the welfare analysis. The full set of model parameters is presented in Table B5.

Given this calibration, Table 4 presents the results comparing the welfare of different trade policies relative to autarky. The columns report changes in various steady-state values relative to autarky given the parameter choices in Table B5. The second row displays the effect of moving from autarky to free trade where imported sheep are 80% the cost in autarky. This leads to a large increase in meat and wool consumption and a reduction in the outside good consumption as the household engages in trade. Overall, this leads to a .9% increase in welfare relative to autarky, which demonstrates how the model captures the basic Ricardian idea of gains from trade. The next row illustrates the negative effects of the trade-induced health externality. In this scenario, imported sheep are still 80% of the cost in autarky, yet 3% of imported sheep are infected with sheep scab. This results in welfare that is .3% higher than autarky and .6% lower than trade with no disease. Row 4 analyzes a policy that resembles the import ban on sheep imports examined in Section 5. In this scenario, imported sheep are still 80% of the cost in autarky, yet a ban on the first exporting country (with $r_1^f = .03$) leads the domestic country to import from a second country where 8% of imported sheep are infected with sheep scab. This results in welfare .7% lower than autarky. The next row compares this to an alternative policy where they continue to trade with Europe, so 3% of imported sheep have sheep scab, yet 2% also have foot-and-mouth. In this scenario welfare increases, and is approximately .1% less than autarky. However, the last row provides an alternative scenario in which the second disease is rinderpest. In this

scenario not banning European sheep would have large negative effects, leading to welfare 2.9% lower than autarky. Overall, this highlights how the effectiveness of trade restrictions at addressing health externalities depends on the underlying disease environment and how economic incentives are influenced by the restrictions.

Table 4: Steady State Welfare of Different Trade Policies Relative to Autarky

	%Δ Welfare	%Δ Sheep	%Δ Cattle	%Δ Mutton	%Δ Wool	%Δ Beef	%Δ Good
Autarky	-	-	-	-	-	-	-
Trade	0.9	0	0	16.2	16.2	0	-7.1
Trade & Disease	0.3	-0.3	0	15.7	14.7	0	-7.2
Ban	-0.7	-0.9	0	14.9	12.1	0	-7.3
No Ban (FMD)	-0.1	-0.5	-0.1	15.1	14.4	-0.6	-7.2
No Ban (Rinderpest)	-2.9	-4.2	-3.9	13.8	13.1	-4.4	-8.2

Note: This table presents the model steady state for several policy scenarios relative to autarky given the calibration of parameters in Table B5. The baseline is autarky with no disease. Column (1) presents the percent change in welfare, defined as the percent change in the consumption of the outside of g_t necessary to make the household indifferent between the autarky equilibrium and the alternative equilibrium. Column (2) reports the percent change in domestic sheep relative to autarky. Column (3) reports the percent change in domestic cattle relative to autarky. Column (3)-(7) report the percent change in household consumption of each good relative to autarky. Row 2 presents the results where livestock imports are 80% of the price in autarky. Row 3 presents the results where livestock imports are 80% of the price in autarky and 3% of imported animals are infected with sheep scab. Row 4 presents the results where results where livestock imports are 80% of the price in autarky and 8% of imported sheep are infected with sheep scab. Row 5 presents the results where 3% of imported sheep are infected with sheep scab and 2% are infected with foot-and-mouth disease. Row 6 presents the results where 3% of imported sheep are infected with sheep scab and 2% are infected with rinderpest.

8 Conclusions

The trade in agricultural products is inherently risky as it can spread diseases, pests, and invasive species across countries. This creates a tradeoff where the gains from trade come at the cost of potential health externalities. The international trade in live animals during the rise of globalization in the nineteenth century provides a useful context to explore this tradeoff and assess trade restrictions designed to address disease transmission from trade.

I find that the port slaughter policies implemented by British officials were effective in reducing disease transmission. These policies restricted the ability for foreign sheep to move inland, requiring that they be slaughtered at the port of entry. Several episodes of port slaughter subjected on foreign sheep reduced the number of sheep scab outbreaks among

domestic flocks. The 1877 episode of port slaughter also had no effect on meat prices. Overall, these results suggest this was an effective policy at reducing the spread of disease from foreign to domestic livestock while also mitigating the negative economic consequences from restricting trade.

In contrast, the import bans Britain placed on European sheep imports starting in 1889 had negative effects on disease transmission and economic costs. The ban on European sheep caused British consumers to substitute toward sheep from the Americas that had higher prevalence of sheep scab. In the years after the import ban, sheep scab outbreaks increased among domestic sheep. The import ban also reduced the supply of sheep leading to higher meat prices in several British cities. Overall, the episode demonstrates how policy design is important when considering trade restrictions aimed to address health externalities from trade. Economic incentives from trade restrictions can have the unintended consequence of worsening disease spread.

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Appendix

A Data Appendix

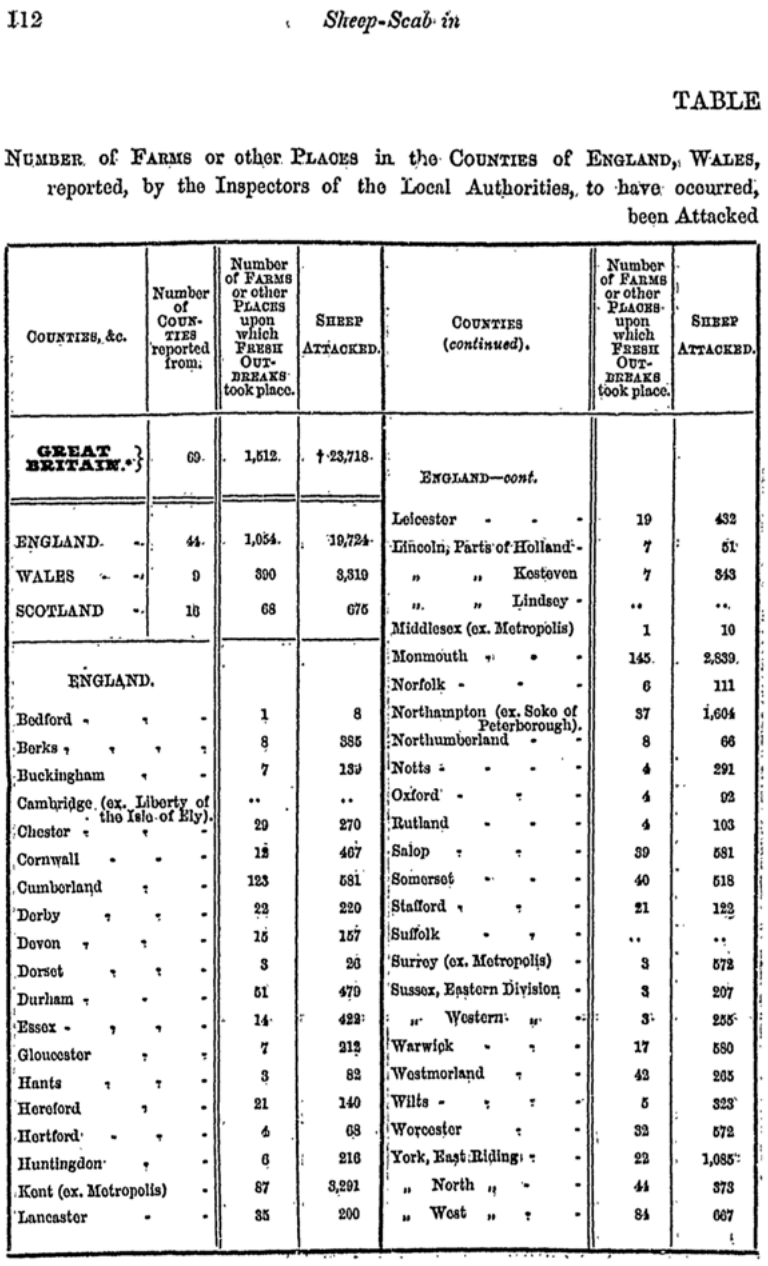
A.1 International Trade Data

This section provides additional details on how the data on international trade is collected. The number of live cattle, sheep, and pigs imported from each country was compiled in the Veterinary Department's annual reports. The following list provides the exact edition which is used to collect data for various years.

- Trade for the years 1875-1891 was taken from: *The Annual Report of the Director of the Director of the Veterinary Department, 1891*, pg. 178-188.
- Trade for the years 1892-1895 was taken from: *Annual Reports of Proceedings under The Diseases of Animals Act, 1894, The Markets and Fairs (Weighing of Cattle) Acts, 1895*, pg. 70-71.
- Trade for the years 1896-1899 was taken from: *Annual Reports of Proceedings under The Diseases of Animals Act, 1894, The Markets and Fairs (Weighing of Cattle) Acts, 1899*, pg. 66.
- Trade for the years 1896-1899 was taken from: *Annual Reports of Proceedings under The Diseases of Animals Act, 1894, The Markets and Fairs (Weighing of Cattle) Acts, 1899*, pg. 66.
- Trade for the years 1900-1902 was taken from: *Annual Reports of Proceedings under The Diseases of Animals Acts, The Markets and Fairs (Weighing of Cattle) Acts, 1902*, pg. 60.

In addition to this exporter-animal level data, for several different years I also digitize data at the exporter-animal-port level that tracks the number of specific types of animals imported into particular parts from each exporting country. This information is also found in each edition of the Veterinary Department's annual reports. Figure A3 provides an example of the data.

Figure A1: Example of Sheep Scab Infections Data



112 *Sheep-Scab in*

TABLE

NUMBER of FARMS or other PLACES in the COUNTIES of ENGLAND, WALES, reported, by the Inspectors of the Local Authorities, to have occurred, been Attacked

COUNTIES, &c.	Number of COUNTIES reported from.	Number of FARMS or other PLACES upon which FRESH OUTBREAKS took place.	SHEEP ATTACKED.
GREAT BRITAIN.*	69.	1,512.	† 23,718.
ENGLAND.	44.	1,054.	19,724.
WALES	9	390	3,319
SCOTLAND	16	68	675
ENGLAND.			
Bedford	1	8	
Berks	8	385	
Buckingham	7	139	
Cambridge (ex. Liberty of the Isle of Ely).	..	..	
Chester	29	270	
Cornwall	12	467	
Cumberland	123	581	
Derby	22	220	
Devon	15	157	
Dorset	3	26	
Durham	51	479	
Essex	14	422	
Gloucester	7	212	
Hants	3	82	
Hereford	21	140	
Hertford	6	68	
Huntingdon	6	216	
Kent (ex. Metropolis)	87	3,291	
Lancaster	35	200	

COUNTIES (*continued*).	Number of FARMS or other PLACES upon which FRESH OUTBREAKS took place.	SHEEP ATTACKED.
ENGLAND—*cont.*		
Leicester	19	432
Lincoln, Parts of Holland	7	51
„ „ Kesteven	7	343
„ „ Lindsey	..	..
Middlesex (ex. Metropolis)	1	10
Monmouth	145	2,839.
Norfolk	6	111
Northampton (ex. Soke of Peterborough).	37	1,604
Northumberland	8	66
Notts	4	291
Oxford	4	92
Rutland	4	103
Salop	39	581
Somerset	40	518
Stafford	21	122
Suffolk	..	..
Surrey (ex. Metropolis)	3	572
Sussex, Eastern Division	3	207
„ Western „	3	255
Warwick	17	580
Westmorland	42	265
Wilts	5	323
Worcester	32	572
York, East Riding	22	1,085
„ North „	44	373
„ West „	84	667

Note: This figure provides an example of the sheep scab infections data digitized for the empirical analysis. The data are taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*.

Figure A2: Example of Data on Infections among Imported Animals

TABLE XXIII.—Table showing the Number of FOREIGN Cattle, Sheep, and Swine affected with any CONTAGIOUS DISEASE, which were Imported into Great Britain, from each COUNTRY, during each of the Years 1891, 1892, 1893, 1894, and 1895.

(*Compiled from the Certificates furnished by the Veterinary Inspectors of the Board of Agriculture.*)

Disease and Class of Animal.	Years.	Argentina.	Australia. (New South Wales.)	Canada.	Chile.	United States of America.	Uruguay.	Total.
Pleuro-Pneumonia (*Cattle.*)	1891	..	..	..	..	4	..	4
	1892	..	..	..	..	33	..	33
	1893	..	..	4	..	36	..	40
	1894	..	..	6	..	5	..	11
	1895	1	18	2	..	5	..	26
Sheep-Scab (*Sheep.*)	1891	3,944	..	..	..	1,880	..	5,824
	1892	1,152	..	..	..	556	..	1,708
	1893	1,653	..	1	120	..	..	1,774
	1894	9,143	..	213	..	6,619	..	15,975
	1895	81,267	..	130	85	1,511	120	83,113
Swine-Fever (*Swine.*)	1891	..	..	..	..	..	..	..
	1892	..	..	..	..	48	..	48
	1893	..	..	..	..	..	..	..
	1894	..	..	..	..	..	..	..
	1895	..	..	..	..	..	..	..

Note: This figure provides an example of the data on infections among animals imported to Britain from specific exporting countries. The data are taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*.

Figure A3: Example of Animal Imports Data by Exporter and Port of Entry

TABLE XV.—NUMBER of FOREIGN CATTLE, SHEEP, and SWINE Imported into EACH

COUNTRIES from which Exported.	LIVERPOOL.			LONDON.		
	Cattle.	Sheep.	Swine.	Cattle.	Sheep.	Swine.
Belgium	...	...	...	...	5,345	31
Channel Islands	...	...	...	...	...	...
Denmark	...	...	...	...	...	...
Germany (ex. Schleswig-Holstein)	...	...	...	...	169,928	...
„ , Schleswig-Holstein	...	...	...	10,136	48,111	...
Iceland	...	7,500	...	...	...	...
Netherlands	...	...	...	31,467	505,814	18,649
Norway	...	...	...	35	...	...
Portugal	1,071	...	...	2,314	...	...
Spain	...	...	...	1,984	...	...
Sweden	...	...	...	2,647	...	...
Canada	22,813	18,593	3	14,321	10,084	...
New Zealand	...	...	...	...	...	...
United States of America	49,164	975	...	34,073	...	...
TOTAL	73,048	27,068	3	96,977	739,282	18,660

COUNTRIES from which Exported.	PORTSMOUTH.			SOUTHAMPTON.		
	Cattle.	Sheep.	Swine.	Cattle.	Sheep.	Swine.
Belgium	...	...	...	...	...	...
Channel Islands	...	...	...	1,798	...	...
Denmark	...	...	...	...	...	...
Germany (ex. Schleswig-Holstein)	...	...	...	...	...	...
„ , Schleswig-Holstein	...	...	...	...	...	...
Iceland	...	...	...	...	...	...
Netherlands	...	...	...	...	...	3
Norway	...	...	...	...	...	...
Portugal	2,103	...	...	566	...	...
Spain	1,140	...	...	...	...	...
Sweden	...	...	...	...	...	...
Canada	...	...	...	...	...	...
New Zealand	...	...	...	...	...	...
United States of America	...	...	...	...	...	...
TOTAL	3,243	...	...	2,364	...	3

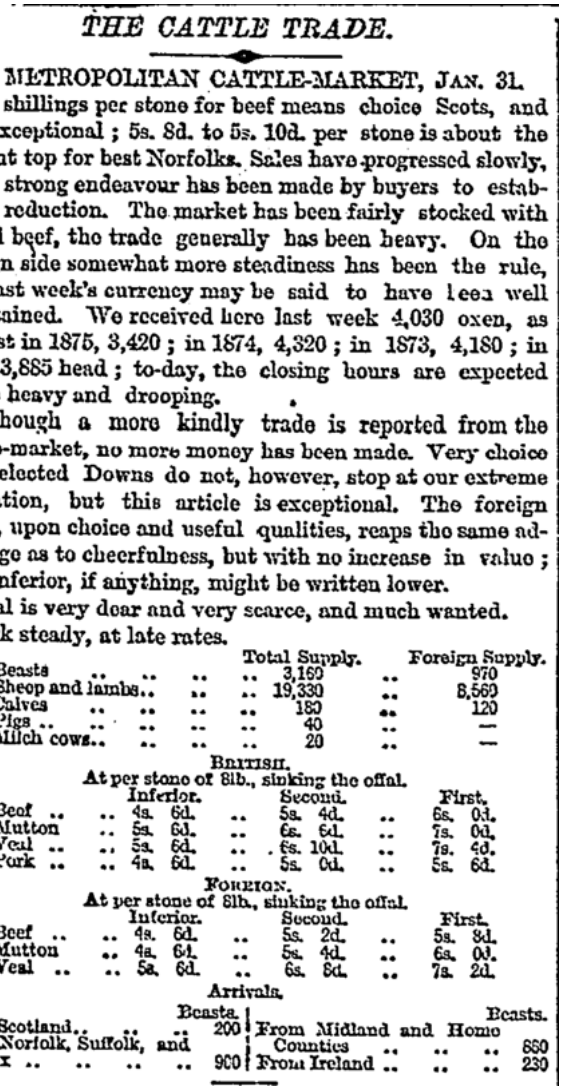
Note: This figure provides an example of the animal imports data. The data report the number of animals imported by exporting countries into particular ports of entry within Britain. The data are taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*.

Figure A4: Example of Data on the Quantity of Domestic Livestock

Per-centage of Corn Crops to Total Acreage under All Kinds of Crops, Bare Fallow, and Grass.	Total and Proportionate Number of Live Stock as Returned upon the 25th of June.								Years.	Counties Proper.
	Horses.		Cattle.		Sheep.		Pigs.			
	Number used solely for Agriculture, &c., as Returned by Occupiers of Land.	Proportionate Number to every 100 Acres under Crops, Bare Fallow, and Grass.	Total Number Returned.	Proportionate Number to every 100 Acres under Crops, Bare Fallow, and Grass.	Total Number Returned.	Proportionate Number to every 100 Acres under Crops, Bare Fallow, and Grass.	Total Number Returned.	Proportionate Number to every 100 Acres under Crops, Bare Fallow, and Grass.		
										ENGLAND.
45·5	10,878	4·2	33,997	13·2	190,019	74·0	30,685	12·0	1874	Bedford.
45·8	11,064	4·3	34,285	13·4	178,662	69·7	27,781	10·8	1875	
40·8	14,442	3·9	37,147	10·1	307,481	83·8	41,421	11·3	1874	Berks.
41·1	14,757	4·0	35,328	9·6	301,084	81·6	35,294	9·6	1875	
34·1	16,575	4·1	70,198	17·6	298,950	74·8	40,569	10·2	1874	Buckingham.
34·3	17,010	4·2	68,831	17·2	292,383	72·9	35,370	8·8	1875	
53·4	25,974	5·4	47,965	10·0	324,962	67·4	46,836	9·7	1874	Cambridge.
54·1	26,959	5·6	47,507	9·8	321,993	66·6	43,687	9·0	1875	
16·2	19,686	3·8	167,336	32·5	122,001	23·7	63,889	12·4	1874	Chester.
16·2	20,499	3·9	162,466	31·0	111,330	21·3	61,209	11·7	1875	
28·3	28,775	5·6	153,766	29·7	441,779	85·2	62,434	12·0	1874	Cornwall.
27·8	29,780	5·7	156,915	29·9	438,921	83·6	56,435	10·7	1875	
18·0	19,077	3·5	126,069	23·1	562,844	103·0	27,117	5·0	1874	Cumberland.
17·7	19,154	3·5	125,374	23·0	511,137	93·7	24,738	4·5	1875	
15·0	18,693	3·7	144,565	28·8	275,483	54·9	41,197	8·2	1874	Derby.
14·7	19,481	3·9	142,658	28·3	261,523	52·1	37,271	7·4	1875	
27·4	49,145	4·6	216,142	20·1	979,150	91·0	94,264	8·8	1874	Devon.
26·9	50,700	4·7	218,153	20·1	976,158	90·1	84,898	7·8	1875	
24·9	14,989	3·2	77,372	16·4	524,297	111·3	42,009	8·9	1874	Dorset.
24·4	15,356	3·2	76,348	16·1	518,316	109·3	40,957	8·6	1875	
24·3	16,648	4·1	64,156	15·8	225,542	55·4	11,602	2·9	1874	Durham.
23·3	17,200	4·2	63,125	15·4	207,599	50·7	11,526	2·8	1875	
51·1	39,980	4·9	80,443	9·8	406,259	49·6	100,641	12·3	1874	Essex.
51·5	40,781	5·0	78,802	9·6	399,453	48·5	90,277	11·0	1875	
27·4	23,371	3·6	120,624	18·8	471,242	73·3	63,292	9·8	1874	Gloucester.
27·7	23,955	3·7	115,822	18·0	453,881	70·6	55,109	8·6	1875	
37·6	27,224	3·9	62,658	9·0	612,889	88·0	71,882	10·3	1874	Hants.
37·4	28,160	4·0	62,132	8·9	596,183	85·2	63,344	9·1	1875	
25·5	19,923	4·6	80,532	18·7	366,118	84·9	28,424	6·6	1874	Hereford.
25·8	20,531	4·7	80,907	18·6	348,035	80·1	24,596	5·7	1875	
44·3	13,185	3·9	33,380	9·9	195,141	57·9	33,062	9·8	1874	Hertford.
45·1	13,625	4·0	32,442	9·6	188,040	55·8	30,650	9·1	1875	
48·7	9,467	4·6	26,345	12·7	154,824	74·5	20,201	9·7	1874	Huntingdon.
49·8	9,798	4·7	26,301	12·6	156,022	75·0	18,801	9·0	1875	
34·4	28,829	4·0	77,832	10·7	1,021,351	141·0	63,599	8·8	1874	Kent.
34·0	29,711	4·1	73,118	10·1	1,007,790	138·7	58,465	8·0	1875	
13·3	32,973	4·4	239,302	31·6	339,357	44·9	39,518	5·2	1874	Lancaster.
13·4	34,348	4·5	231,057	30·3	314,664	41·3	38,443	5·0	1875	

Note: This figure provides an example of the data on the number of livestock from the British agricultural census. Data are digitized from various years of the *Agricultural Returns of Great Britain*.

Figure A5: Example of Data on Meat Prices in London



THE CATTLE TRADE.

METROPOLITAN CATTLE-MARKET, JAN. 31.

Six shillings per stone for beef means choice Scots, and it is exceptional; 5s. 8d. to 5s. 10d. per stone is about the current top for best Norfolks. Sales have progressed slowly, and a strong endeavour has been made by buyers to establish a reduction. The market has been fairly stocked with useful beef, the trade generally has been heavy. On the foreign side somewhat more steadiness has been the rule, and last week's currency may be said to have been well maintained. We received here last week 4,030 oxen, as against in 1875, 3,420; in 1874, 4,320; in 1873, 4,180; in 1872, 3,885 head; to-day, the closing hours are expected to be heavy and drooping.

Although a more kindly trade is reported from the Sheep-market, no more money has been made. Very choice and selected Downs do not, however, stop at our extreme quotation, but this article is exceptional. The foreign trade, upon choice and useful qualities, reaps the same advantage as to cheerfulness, but with no increase in value; and inferior, if anything, might be written lower.

Veal is very dear and very scarce, and much wanted.

Pork steady, at late rates.

	Total Supply.	Foreign Supply.
Beasts	3,160	970
Sheep and lambs	19,330	8,560
Calves	180	120
Pigs	40	—
Milch cows	20	—

BRITISH.

At per stone of 8lb., sinking the offal.

	Inferior.	Second.	First.
Beef	4s. 6d.	5s. 4d.	6s. 0d.
Mutton	5s. 6d.	6s. 6d.	7s. 0d.
Veal	5s. 6d.	6s. 10d.	7s. 4d.
Pork	4s. 6d.	5s. 0d.	5s. 6d.

FOREIGN.

At per stone of 8lb., sinking the offal.

	Inferior.	Second.	First.
Beef	4s. 6d.	5s. 2d.	5s. 8d.
Mutton	4s. 6d.	5s. 4d.	6s. 0d.
Veal	5s. 6d.	6s. 8d.	7s. 2d.

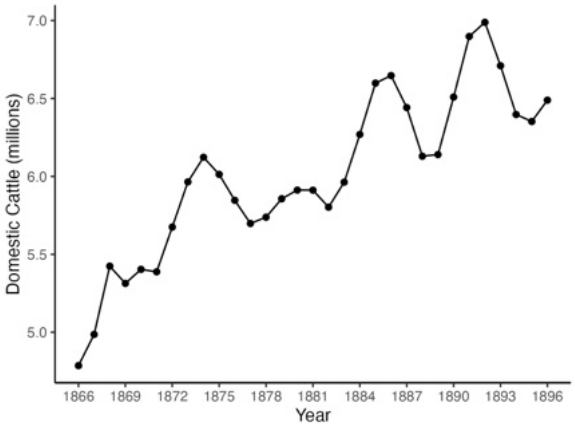
Arrivals.

	Beasts.		Beasts.
From Scotland	200	From Midland and Home Counties	880
From Norfolk, Suffolk, and Essex	900	From Ireland	230

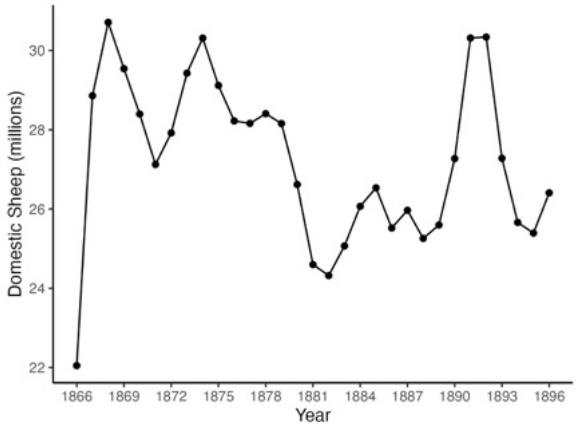
Note: This figure provides an example of the data on meat prices in London reported in local newspapers. The data are taken from various editions of *The Times*.

Figure A6: Total Domestic Cattle & Sheep in Great Britain Over Time

(a) Cattle



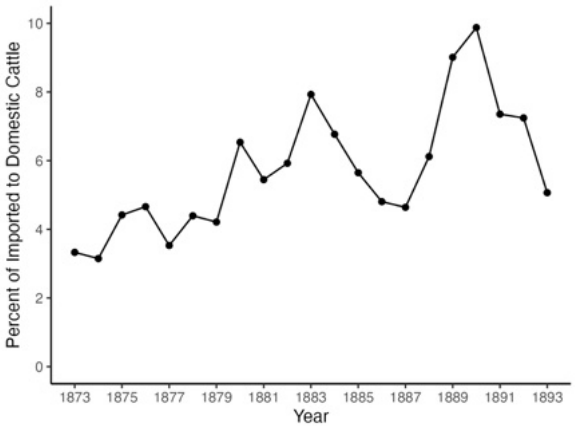
(b) Sheep



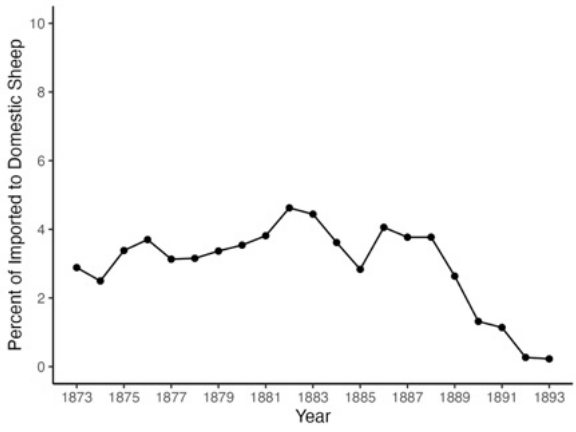
Note: Data are digitized from various years of the *Agricultural Returns of Great Britain*. The figures report all animals from England, Wales, and Scotland.

Figure A7: Imported Relative to Domestic Animals Over Time

(a) Cattle



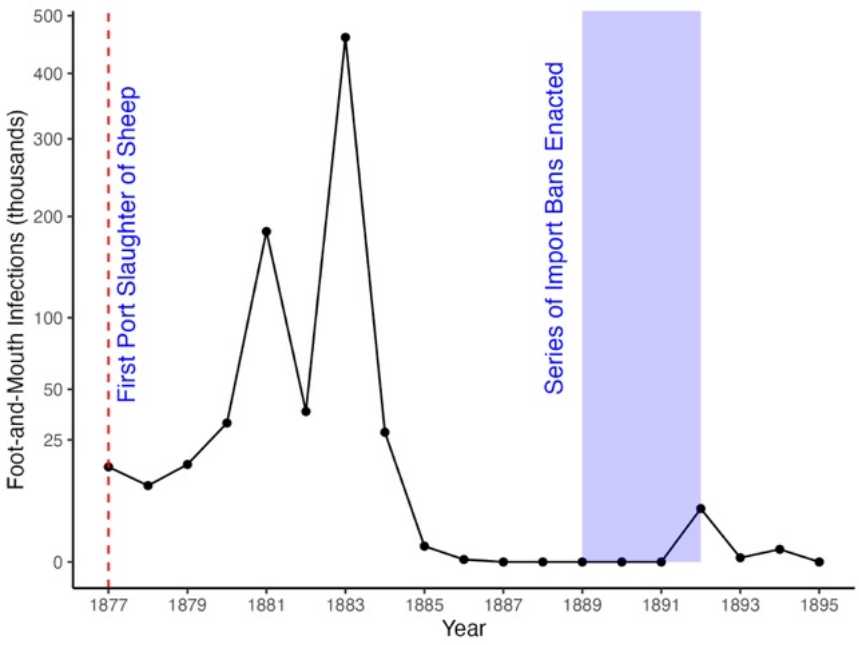
(b) Sheep



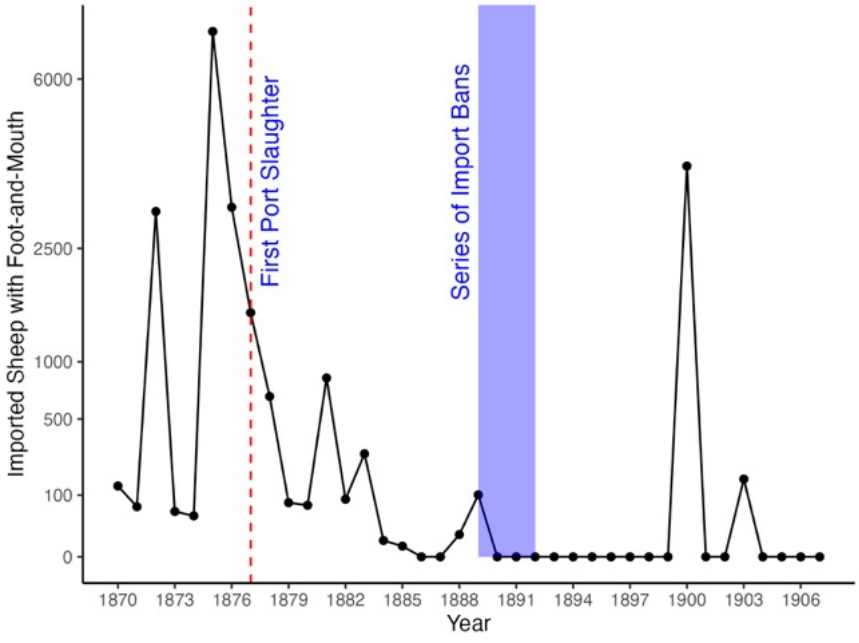
Note: This figure plots the size of the annual imported animals relative to the domestic stock in percentage terms. Data on the number of annual imported animals is taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*. Data on the number of domestic livestock is taken from the *Agricultural Returns of Great Britain*.

Figure A8: Foot-and-Mouth Infections in Domestic and Imported Animals Over Time

(a) Foot-and-Mouth Infections in Domestic Animals

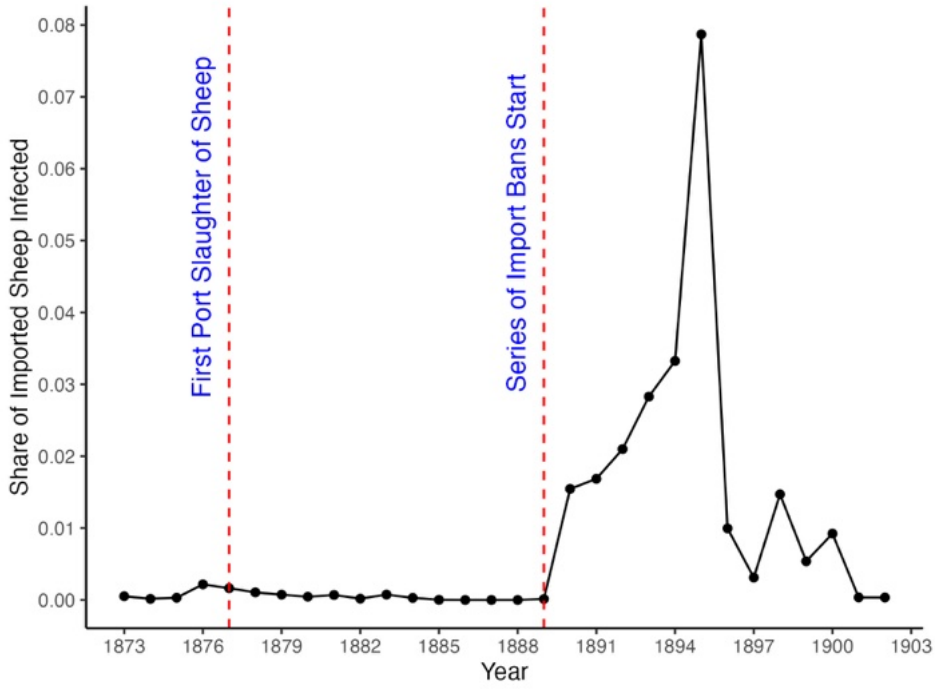


(b) Foot-and-Mouth Infections in Imported Sheep



Note: This figure shows foot-and-mouth disease infections among domestic and imported animals over time. Panel (a) shows the number of infections in domestic animals over time. The total combines infections among cattle, sheep, swine, and other hoofed animals. Panel (b) shows the number of infected imported sheep over time. The red, dashed vertical line corresponds to the year when the first set of port slaughter trade restrictions on sheep imports were implemented. The blue, shaded rectangle corresponds to the period when a series of permanent import bans on sheep from continental European countries were enacted.

Figure A9: Share of Imported Sheep Infected with Sheep Scab



Note: This figure displays the share of imported animals that were infected with sheep scab over time. The dashed vertical lines indicate the years when the trade restrictions were implemented. The data are taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*.

B Results Appendix

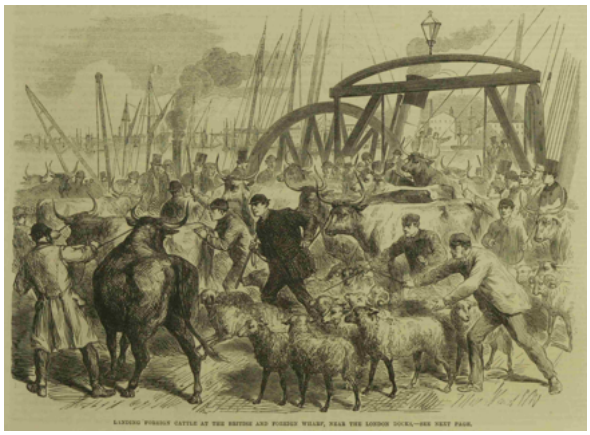
B.1 Health Effects of the Trade Restrictions

Figure B1: Illustration of the Nineteenth Century Trade in Live Animals

(a) Animals in transit from Rotterdam to London



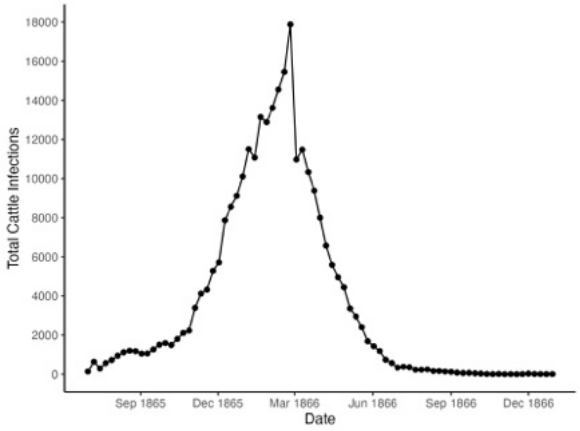
(b) Animals being processed in London



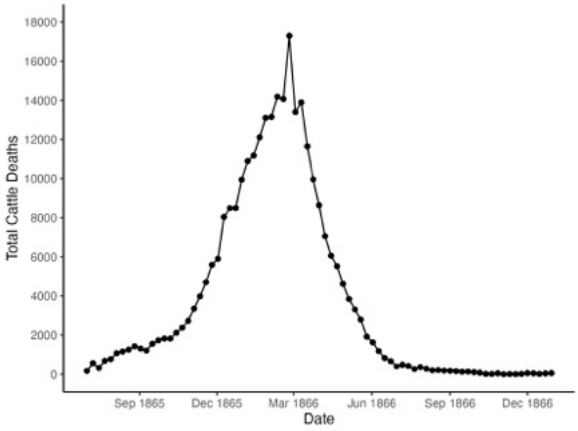
Note: This figure displays images from the *London Illustrated New* depicting the trade in live animals. Panel (a) shows animals aboard a ship in transit from Rotterdam to London. Panel (b) shows animals being processed upon arrival in London.

Figure B2: Cattle Infections and Deaths during the Rinderpest Cattle Plague, 1865-67

(a) Cattle Infections



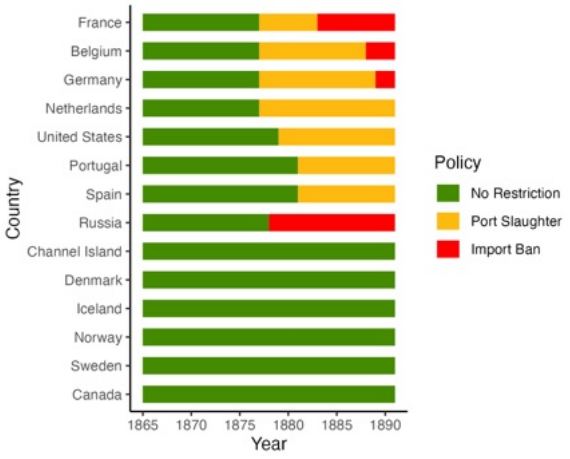
(b) Cattle Deaths



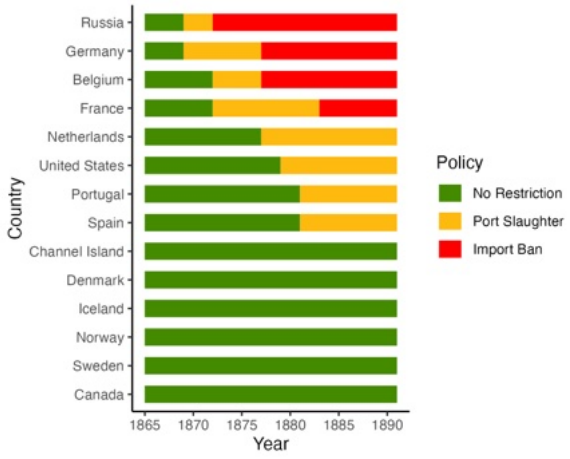
Note: This figure presents weekly data related to the 1865 outbreak of rinderpest. Panel (a) shows the number of weekly infections. Panel (b) shows the number of cattle deaths which combine deaths from the disease as well as animals culled to prevent further disease spread. The data are digitized from: *"The Report on the Cattle Plague in Great Britain, During the Years 1865, 1866, and 1867"*.

Figure B3: The Timing of Trade Restrictions in Britain by Exporter and Animal

(a) Policies Impacting Sheep



(b) Policies Impacting Cattle



Note: This figure displays the timing of when trade restrictions were implemented on live animal imports to Britain. Panel (a) shows the timing of policies targeted toward sheep imports. Panel (b) shows the timing of policies targeted toward cattle imports. Policies were implemented at the exporter-animal level. Green corresponds to no trade restrictions, yellow to port slaughter, and red to complete import bans. The timing of the policies are taken from various editions of the *Annual Reports of the Veterinary Department of the Privy Council*.

Table B1: Effect of the European Sheep Import Bans on Domestic Sheep Scab Infections

	Dependent variable:					
	Infections				Infections Per Capita	
	(1)	(2)	(3)	(4)	(5)	(6)
$post_t \times proximity_c$	234.599***	240.706***	250.559***	258.872***	111.733***	106.152***
	(61.954)	(59.273)	(60.570)	(59.153)	(27.131)	(24.647)
$sheep_{ct}$			0.424	0.458		
			(0.335)	(0.373)		
Dep. Var. Mean	390.954	403.837	392.931	407.208	159.214	161.71
Observations	1,537	935	1,529	927	1,529	927
R^2	0.627	0.701	0.627	0.702	0.373	0.625
Sample	Full	Pre-Port Slaughter	Full	Pre-Port Slaughter	Full	Pre-Port Slaughter

Note: This table presents the results for the effect of the import bans on domestic sheep scab infections by estimating equation (1). The outcome in columns 1-4 is the number of sheep infected. The outcome in columns 5-6 is the number of sheep infected per 100,000 sheep. The full sample uses data from 1885-1902. The pre-port slaughter sample uses data from 1885-1895 which restricts to the period prior to the port slaughter on Canadian and US sheep on January 1, 1896. Columns 3 and 4 control for the number of sheep (in thousands). The data are at the county-year level and include all counties in England, Wales, and Scotland. Standard errors are clustered at the county-level. *** p<0.01, ** p<0.05, * p<0.1.

Table B2: Effect of the European Sheep Import Bans on Sheep Scab Infection, Robustness to Different Treatment Definitions

	Dependent variable:					
	Farm Outbreaks			Infections		
	(1)	(2)	(3)	(4)	(5)	(6)
$proximity_c$ (Main)	10.086***			258.872***		
	(3.363)			(59.153)		
$proximity_c$ (Liverpool)		16.681***			256.305***	
		(2.822)			(59.048)	
$proximity_c$ (London)			6.061*			233.973***
			(3.399)			(60.414)
$sheep_{ct}$	0.036*	0.020	0.034*	0.458	0.131	0.466
	(0.020)	(0.014)	(0.020)	(0.373)	(0.303)	(0.394)
Dep. Var. Mean	23.709	23.709	23.709	407.208	407.208	407.208
Observations	925	925	925	927	927	927
R^2	0.824	0.830	0.822	0.702	0.702	0.700

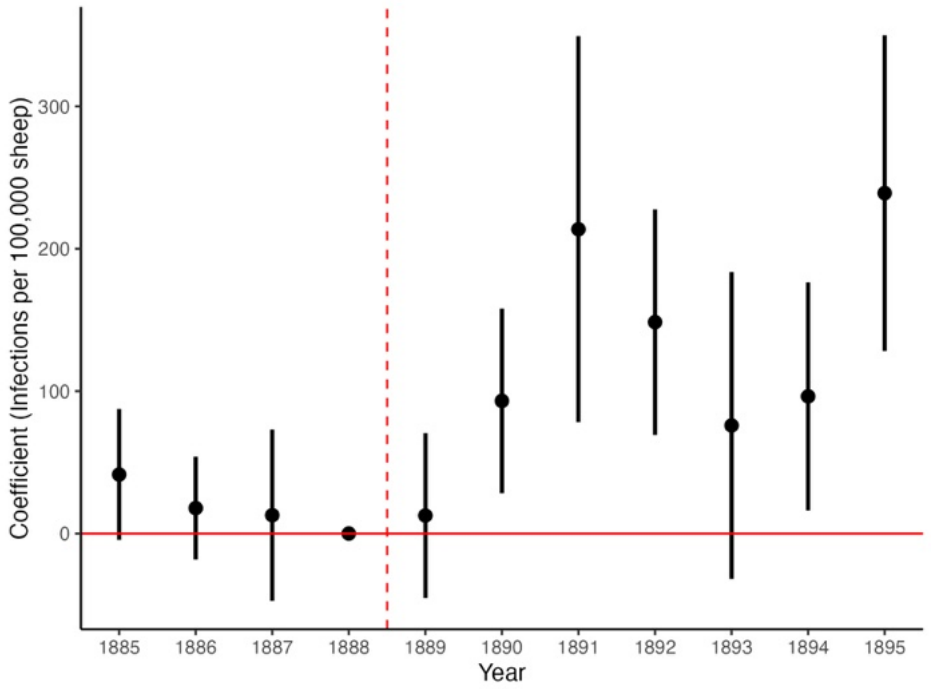
Note: This table presents the results for the effect of the import bans on sheep scab infection by estimating equation (1) for several alternative treatment definitions. In columns 1-3, the outcome is the number of sheep scab outbreaks on farms. In columns 4-6, the outcome is the number of sheep infected with sheep scab. Columns 1 and 4 present the results for the main treatment definition: if the county is below median distance to either Liverpool or London. Columns 2 and 5 present the results if treatment is defined as below median distance to Liverpool. Columns 3 and 6 present the results if treatment is defined as below median distance to London. All specifications control for the number of sheep at the county-level (in thousands). The data are at the county-year level and include all counties in England, Wales, and Scotland. Standard errors are clustered at the county-level. *** p<0.01, ** p<0.05, * p<0.1.

Table B3: Effect of the European Sheep Import Bans on Sheep Scab Infection, Robustness to Using Distance to Key Importing Ports to Define Treatment

	Dependent variable:					
	Farm Outbreaks			Infections		
	(1)	(2)	(3)	(4)	(5)	(6)
$distance_c$ (Main)	-0.034^{***}			-0.727^{***}		
	(0.009)			(0.139)		
$distance_c$ (Liverpool)		-0.060^{***}			-0.921^{***}	
		(0.014)			(0.161)	
$distance_c$ (London)			-0.015^{***}			-0.503^{***}
			(0.005)			(0.109)
$sheep_{ct}$	0.034^{*}	0.026	0.035^{*}	0.378	0.214	0.467
	(0.019)	(0.016)	(0.020)	(0.366)	(0.327)	(0.386)
Dep. Var. Mean	23.709	23.709	23.709	407.208	407.208	407.208
Observations	925	925	925	927	927	927
R^2	0.824	0.829	0.822	0.699	0.701	0.700

Note: This table presents the results for the effect of the import bans on sheep scab infection by estimating equation (1) using distance to key importing ports as an alternative treatment definition. In columns 1-3, the outcome is the number of sheep scab outbreaks on farms. In columns 4-6, the outcome is the number of sheep infected with sheep scab. Columns 1 and 4 present the results when treatment is defined as the minimum distance to either Liverpool or London. Columns 2 and 5 present the results if treatment is defined as below median distance to Liverpool. Columns 3 and 6 present the results if treatment is defined as below median distance to London. All specifications control for the number of sheep at the county-level (in thousands). The data are at the county-year level and include all counties in England, Wales, and Scotland. Standard errors are clustered at the county-level. *** p<0.01, ** p<0.05, * p<0.1.

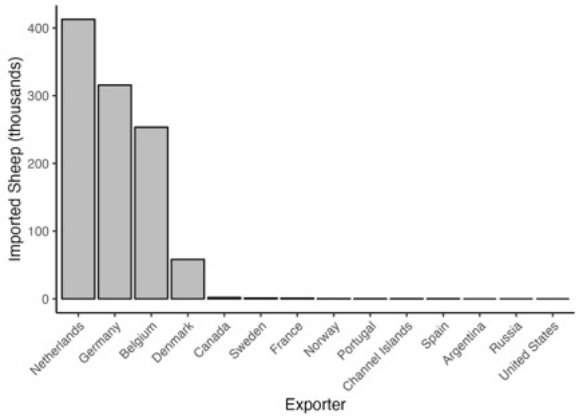
Figure B4: Effect of the European Sheep Import Bans on Sheep Scab Infections per Capita



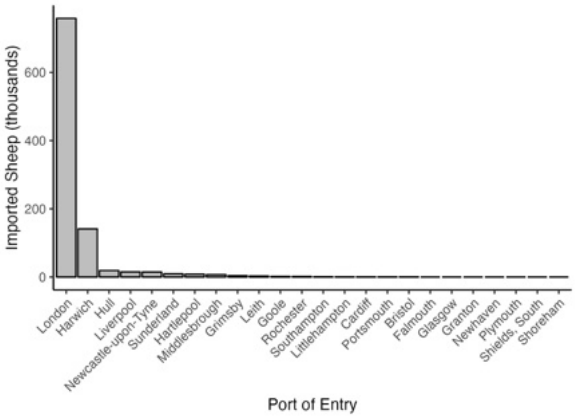
Note: This figure presents the event study plot for the effect of the European sheep import bans on sheep scab infections per capita. The red, dashed line corresponds to the period where import bans on European sheep begin to be implemented. The outcome is the number of sheep scab infections per 100,000 domestic sheep at the county-level. Standard errors are clustered at the county-level.

Figure B5: Sheep Imports Prior to 1877 Port Slaughter Trade Restrictions

(a) Total Sheep Imports by Exporter (1876)



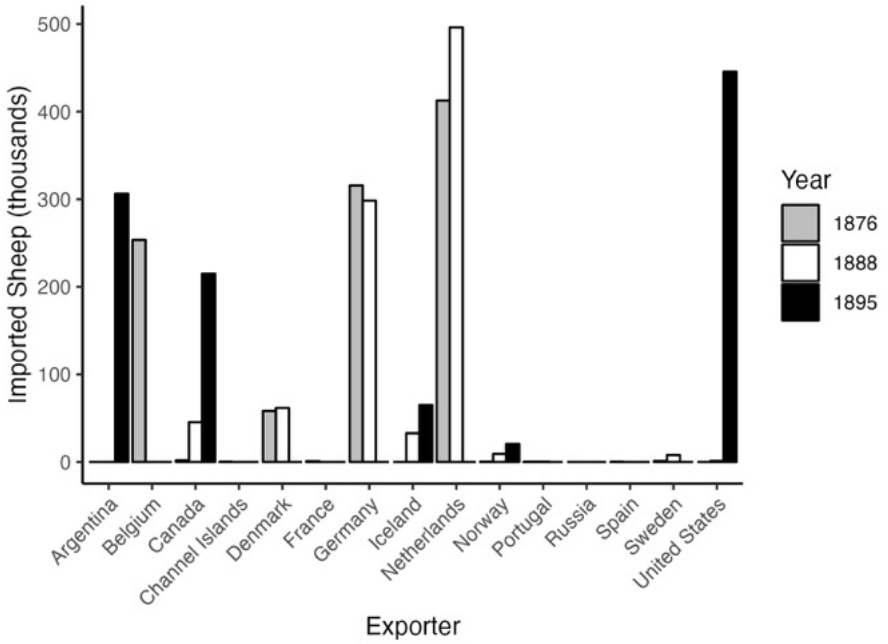
(b) Imports to Ports from Exporters Facing Port Slaughter (1876)



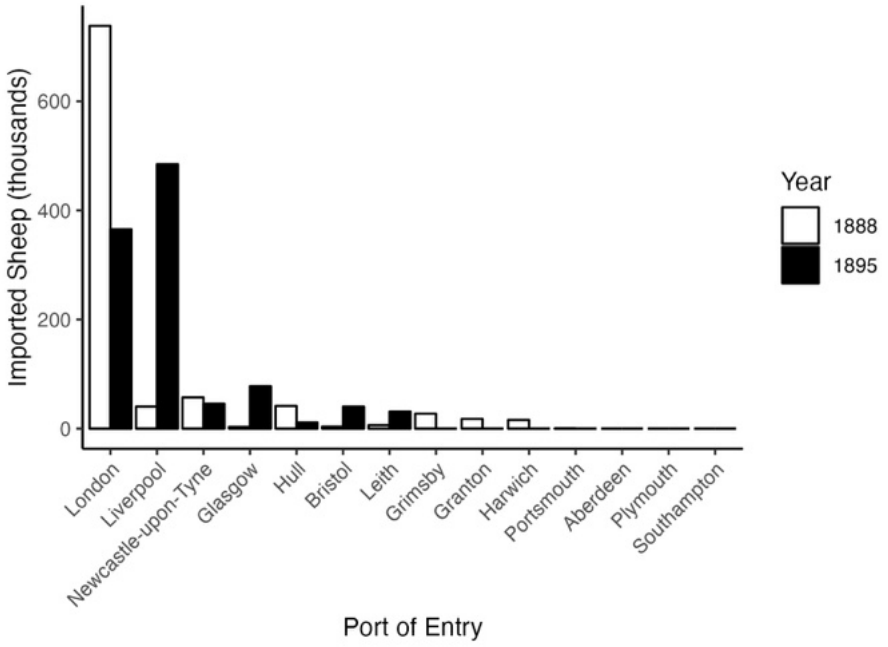
Note: This figure presents data on sheep imports in 1876, the year prior to the first set of port slaughter policies. Panel (a) shows the number of sheep imported into Britain by each exporting country. Panel (b) shows the number of sheep imported to specific ports within Britain from countries subjected to port slaughter (Germany, Netherlands, France, Belgium, Russia).

Figure B6: Sheep Imports around the 1889-1892 Import Ban Trade Restrictions

(a) Sheep Imports by Exporter for Key Dates



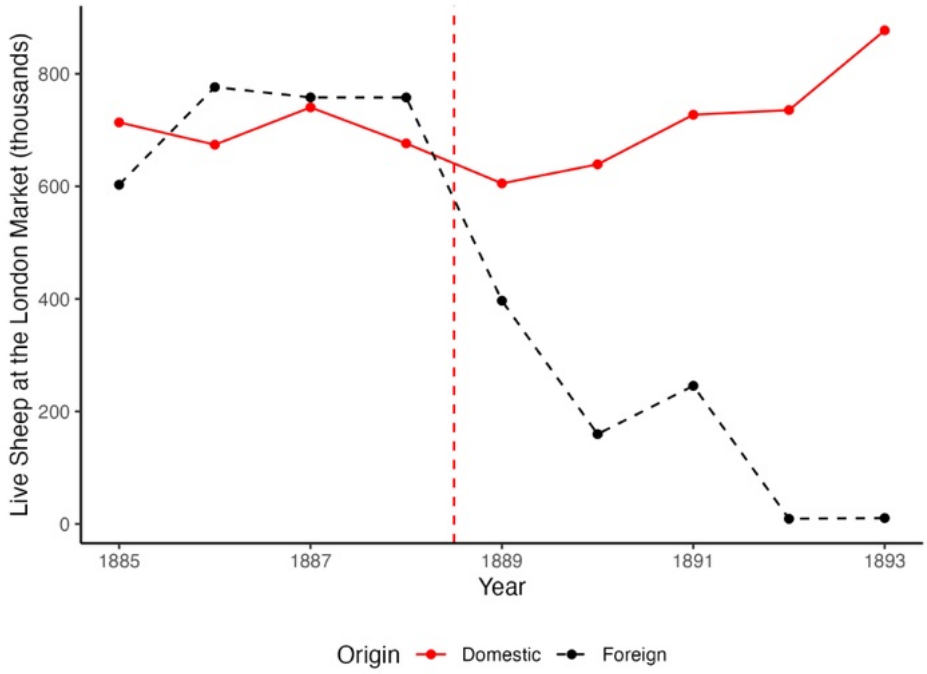
(b) Imports to Specific Ports Before & After the Import Bans on European Sheep



Note: This figure presents sheep imports by exporting country and port of entry for several key dates around trade restrictions. Panel (a) shows the number of imported sheep by exporting country for three key dates: just prior to the initial set of port slaughter trade restrictions (1876), just prior to the beginning of import bans on European sheep (1888), and after Britain started to substitute to new exporting countries for sheep (1895). Panel (b) displays the specific ports where sheep entered Britain before and after the import bans on European sheep between 1889 and 1892.

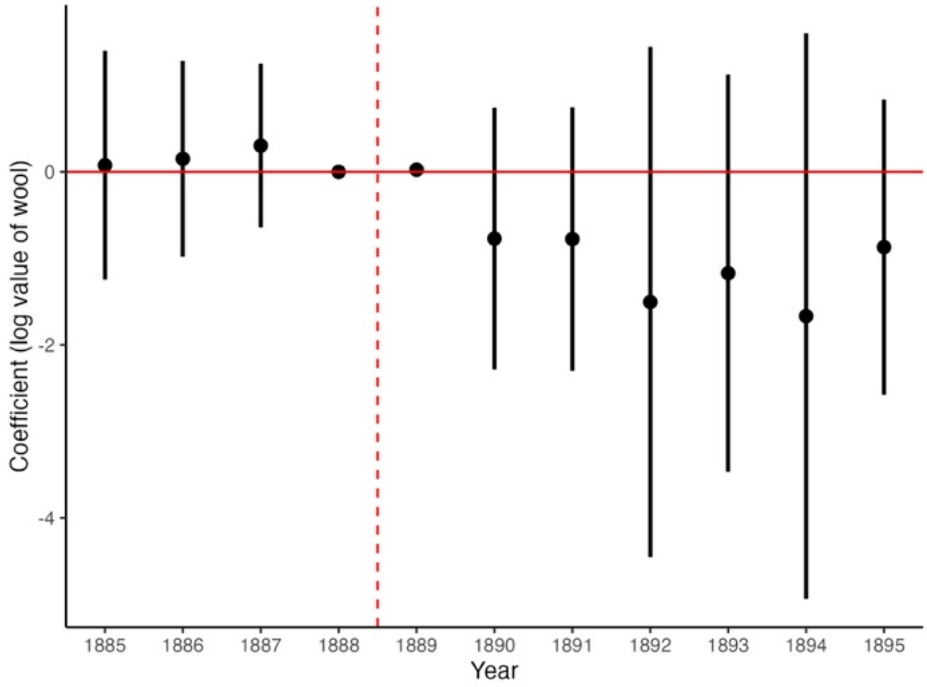
B.2 Economic Effects of the Trade Restrictions

Figure B7: Number of Sheep Sold at the London Livestock Market by Origin Status



Note: This figure displays the number of sheep that were sold at the London livestock market for several years around the import bans on European sheep. The solid, red line displays the number of domestic sheep sold. The dashed, black line shows the number of foreign sheep sold. The dashed, vertical line indicates the year when the series of import bans start. The data are taken from various editions of the *Annual Report of the Veterinary Department of the Privy Council*.

Figure B8: Effect of the European Sheep Import Bans on Wool Exports (Value in Pounds)



Note: This figure presents the event study plot for the effect of the European sheep import bans on the value of wool exports. The red, dashed line corresponds to the period where import bans on European sheep begin to be implemented. The outcome is the log value (in pounds) of wool exports at the port-level. Standard errors are clustered at the port-level.

Table B4: Effect of the European Sheep Import Bans on Wool Exports

	Dependent variable:	
	(1)	(2)
	Weight	Value
$\mathbb{1}\{t > 1888\}_t \times treat_p$	-1.445^{**}	-1.097^{**}
	(0.627)	(0.472)
Dep. Var. Mean	9.624	7.212
Observations	233	230
R^2	0.807	0.842

Note: This table presents the results for the effect of the import bans on wool exports by estimating 3. In column 1, the outcome is the log weight (in pounds) of wool exports. In column 2, the outcome is the log value (in pounds) of wool exports. Data are at the port-year level from 1885 to 1895. Standard errors are clustered at the port-level. *** p<0.01, ** p<0.05, * p<0.1.

C Model Appendix

C.1 Solving for the Steady State

C.1.1 Steady State of the Autarky Model

This section solves for the steady state of the model when there is no international trade or disease. This steady state will be the benchmark comparison for the counterfactuals.

We first solve for the steady state number of sheep and cattle. In autarky with no disease, there are only healthy sheep and cattle. So given the laws of motion in equations (8 & 9), the steady state values of each animal can be written as:

$$s = \varphi(\lambda L)^{\sigma} s^{1-\sigma} \implies s^* = \varphi^{\frac{1}{\sigma}} \lambda L \tag{28}$$

$$c = \varphi((1-\lambda)L)^{\sigma} c^{1-\sigma} \implies c^* = \varphi^{\frac{1}{\sigma}} (1-\lambda) L \tag{29}$$

Given the Cobb-Douglas preferences, the household will optimally consume a fixed share of total income on each good.

$$b_t = \frac{\alpha_1 I}{p_{bt}}, \quad m_t = \frac{\alpha_2 I}{p_{mt}}, \quad w_t = \frac{\alpha_3 I}{p_{wt}}, \quad g_t = \alpha_4 I \tag{30}$$

Where total income combines wage income, rents from selling adult sheep for slaughter, and rents for selling adult cattle for slaughter:

$$I = AN + p_{st} s_t + p_{ct} c_t \tag{31}$$

Since there is no disease that could destroy output, from equations (12 – 14) the amount of wool and mutton produced equals the number of sheep $w^* = m^* = s^*$. Similarly, the amount of beef equals the number of cattle $b^* = c^*$. Given that there is no trade, market clearing also implies these are the amount of each good consumed.

The firm's optimization problem gives a relationship between the price of livestock and the price of agricultural goods. Given no domestic disease, firm optimization from equation (15) implies $p_{st} = p_{wt} + p_{mt}$ and $p_{ct} = p_{bt}$.

To solve for equilibrium goods prices, first substitute the steady state values for cattle and sheep, and $p_{st} = p_{wt} + p_{mt}$ and $p_{ct} = p_{bt}$ from the firm's problem, into the expression for income. This yields the following equation for income.

$$I = AN + (p_{mt} + p_{wt}) s^* + p_{bt} c^* \tag{32}$$

Finally, substitute this expression for income and the market clearing values of each good ($b^* = c^*$, $w^* = m^* = s^*$) into the optimal consumption equations. This yields a system of four equations that can be used to solve for the steady state prices of each good in autarky as a function of the model parameters.

$$p_b^a = \frac{\alpha_1 AN}{\alpha_4 \varphi^{\frac{1}{\sigma}}(1-\lambda)L}, \quad p_m^a = \frac{\alpha_2 AN}{\alpha_4 \varphi^{\frac{1}{\sigma}}\lambda L}, \quad p_w^a = \frac{\alpha_3 AN}{\alpha_4 \varphi^{\frac{1}{\sigma}}\lambda L}, \quad p_g^a = 1 \tag{33}$$

Before moving to the model with trade, it is useful to note the steady state price of sheep in autarky. The autarky price is important for introducing trade in the model. Given the firm's problem, we know the price of sheep with no disease is $p_{st} = p_{mt} + p_{wt}$, so the steady state autarky price of sheep is given by:

$$p_s^a = p_m^a + p_w^a = \frac{(\alpha_2 + \alpha_3)AN}{\alpha_4 \varphi^{\frac{1}{\sigma}}\lambda L} \tag{34}$$

C.1.2 Steady State of the Model with Trade and No Disease

This section discusses the equilibrium of the model where trade in sheep is allowed, but there is no disease. The equilibrium is similar to the autarky steady state, with a few differences that I will highlight.

First, since there is no disease, the steady state number of domestic sheep and cattle is the same as in autarky.

A key difference is that the household imports a number of sheep s^f at the price of sheep in the exporting country, p_s^T, that we assume to be below the equilibrium price of sheep in autarky $p_s^T < p_s^a$

The household still consumes a fixed share of their income on each good. However, the prices of the goods are different, given trade, which affects both optimal consumption and the household's income.

$$b_t = \frac{\alpha_1 I}{p_{bt}^T}, \quad m_t = \frac{\alpha_2 I}{p_m^T}, \quad w_t = \frac{\alpha_3 I}{p_w^T}, \quad g_t = \alpha_4 I \tag{35}$$

Total income takes the same form as before, except the prices are different given trade.

$$I = AN + p_s^T s_t + p_c^T c_t \tag{36}$$

To finish specifying the equilibrium, it is necessary to determine the new prices under trade: $p_b^T, p_c^T, p_m^T, p_w^T$. We first start by solving for the wool and mutton prices (p_m^T, p_w^T). First, since there is no disease, the market clearing conditions and production technologies for wool and mutton imply:

$$w_t = m_t = s_t + s^f \tag{37}$$

Substituting this into the firm's problem yields the following relationship between prices $p_s^T = p_m^T + p_w^T$. Next, given that wool and mutton consumption is equal when there is no disease, from equation (35) we have:

$$m_t = w_t \implies \frac{\alpha_2 I}{p_m^T} = \frac{\alpha_3 I}{p_w^T} \tag{38}$$

Substituting in the price rule from the firm problem yields the following equations for the prices of mutton and wool:

$$p_m^T = \frac{\alpha_2 p_s^T}{\alpha_2 + \alpha_3} \qquad\qquad p_w^T = \frac{\alpha_3 p_s^T}{\alpha_2 + \alpha_3} \tag{39}$$

Finally, we need to solve for the prices of cattle and beef (p_b^T, p_c^T). First, given no disease, note that from the firm's problem we have $p_b^T = p_c^T$. Second, note that since there is no trade in cattle, domestic production equals consumption: $b_t = c_t$. Substituting these into the household consumption for beef from equation (35) yields the following price:

$$p_c^T = p_b^T = \frac{\alpha_1 (AN + p_s^T s^*)}{c^* - \alpha_1 c^*} \tag{40}$$

C.1.3 Steady State of the Model with Trade and Disease

This section presents the equilibrium of the model where trade in sheep is allowed and those sheep can be infected with disease.

To solve for the equilibrium of the model with trade and disease, we first derive the steady state number of healthy and infected livestock. We first make the assumption that $\beta_1 = \beta_2 = 1$. Then suppose that in steady state the share of "old" livestock (those consumed at time t) that are infected with each disease will be a constant κ_1 and κ_2. Then based on the laws of motion for sheep, steady state values would imply:

$$s = \varphi(\lambda L)^\sigma (h_s + \theta_1 i_{s1} + \theta_2 i_{s2} + \theta_3 i_{s3})^{1-\sigma} \tag{41}$$

$$h_s = s - i_{s1} - i_{s2} - i_{s3} \tag{42}$$

$$i_{s1} = \underbrace{\left(\frac{r_1^f s^f + i_{s1} + i_{s3}}{s^f + s}\right)}_{\kappa_1} s - i_{s3} = \kappa_1 s - i_{s3} \tag{43}$$

$$i_{s2} = \underbrace{\left(\frac{r_2^f s^f + i_{c2} + i_{s2} + i_{s3}}{s^f + s + c}\right)}_{\kappa_2} s - i_{s3} = \kappa_2 s - i_{s3} \tag{44}$$

$$i_{s3} = \kappa_1 \kappa_2 s \tag{45}$$

Similarly, based on the laws of motion for cattle, steady state values would imply the following equations. Note that cattle can only be infected with disease 2 (either rinderpest or foot-and-mouth) and not disease 1 (sheep scab).

$$c = \varphi((1-\lambda)L)^{\sigma}(h_c + \theta_2 i_{c2})^{1-\sigma} \tag{46}$$

$$h_c = c - i_{c2} \tag{47}$$

$$i_{c2} = \underbrace{\left(\frac{r_2^f s^f + i_{c2} + i_{s2} + i_{s3}}{s^f + s + c}\right)}_{\kappa_2} c = \kappa_2 c \tag{48}$$

Substituting the equations for the infected and healthy into the law of motion and simplifying yields:

$$s = \varphi^{\frac{1}{\sigma}} \lambda L \Big(1 - \kappa_1(1-\theta_1) - \kappa_2(1-\theta_2) + \kappa_1\kappa_2(1-\theta_1-\theta_2+\theta_3)\Big)^{\frac{1-\sigma}{\sigma}} \tag{49}$$

$$c = \varphi^{\frac{1}{\sigma}} (1-\lambda) L \Big(1 - \kappa_2(1-\theta_2)\Big)^{\frac{1-\sigma}{\sigma}} \tag{50}$$

To solve for the steady-state livestock, we need to determine the values for κ_1, κ_2. Consider κ_1. Substituting in the steady state equations for the number of infected animals yields:

$$\kappa_1 = \frac{r_1^f s^f + i_{s1} + i_{s3}}{s^f + s} = \frac{r_1^f s^f + \kappa_1 s - \kappa_1\kappa_2 s + \kappa_1\kappa_2 s}{s^f + s} \implies \kappa_1 = r_1^f \tag{51}$$

A similar exercise can solve for the value of κ_2, in which both sheep and cattle can be infected:

$$\kappa_2 = \frac{r_2^f s^f + i_{c2} + i_{s2} + i_{s3}}{s^f + s + c} = \frac{r_2^f s^f + \kappa_2 c + \kappa_2 s - \kappa_1\kappa_2 s + \kappa_1\kappa_2 s}{s^f + s + c} \implies \kappa_2 = r_2^f \tag{52}$$

Therefore, when $\beta_1 = \beta_2 = 1$, the rate of disease in the domestic economy converges to the disease rate in the foreign country they trade with. The steady-state level of livestock is given by:

$$s^* = \varphi^{\frac{1}{\sigma}} \lambda L \Bigg(1 - \underbrace{r_1^f(1-\theta_1)}_{\text{disease 1 penalty}} - \underbrace{r_2^f(1-\theta_2)}_{\text{disease 2 penalty}} + \underbrace{r_1^f r_2^f(1-\theta_1-\theta_2+\theta_3)}_{\text{comorbidity term}}\Bigg)^{\frac{1-\sigma}{\sigma}} \tag{53}$$

$$c^* = \varphi^{\frac{1}{\sigma}} (1-\lambda) L \Bigg(1 - \underbrace{r_2^f(1-\theta_2)}_{\text{disease 2 penalty}}\Bigg)^{\frac{1-\sigma}{\sigma}} \tag{54}$$

Given these equations, we can also calculate the steady state number of healthy and infected sheep and cattle as a function of total livestock:

$$i_{s1} = r_1^f s^* - i_{s3}, \quad i_{s2} = r_2^f s^* - i_{s3}, \quad i_{s3} = r_1^f r_2^f s^*, \quad h_c = s^* - i_{s1} - i_{s2} - i_{s3} \tag{55}$$

$$i_{c2} = r_2^f c^*, \quad h_c = c^* - i_{c2} \tag{56}$$

Moving on to the household problem, as in the model with trade and no disease, the household still consumes a fixed share of their income on each good.

$$b_t = \frac{\alpha_1 I}{p_{bt}^T}, \quad m_t = \frac{\alpha_2 I}{p_m^T}, \quad w_t = \frac{\alpha_3 I}{p_w^T}, \quad g_t = \alpha_4 I \tag{57}$$

Total income takes the same form as before: combining wage income, income from selling sheep for slaughter, and income from selling cattle for slaughter.

$$I = AN + p_s^T s_t + p_c^T c_t \tag{58}$$

To finish specifying the equilibrium, it is necessary to determine the new prices under trade: $p_b^T, p_c^T, p_m^T, p_w^T$. We will start with the prices for mutton and wool. Unlike the model with trade and no disease, now disease is going to reduce the amount of wool and mutton produced from a sheep, so $w_t^d + w_t^f \neq s^d + s^f$. We start by calculating the amount of wool and mutton produced from domestic sheep. To do this, we substitute the steady steady number

of healthy and infected livestock from equations (55, 56) into the production equations for wool and mutton in equations (12, 13). After simplifying, the steady state domestic wool and mutton production is given by the following equations.

$$w_d^* = s^* \left(1 - r_1^f \left(1 - \delta_1^w\right) - r_2^f \left(1 - \delta_2^w\right) + r_1^f r_2^f \left(1 - \delta_1^w - \delta_2^w + \delta_3^w\right) \right) := s^* \Delta_w \tag{59}$$

$$m_d^* = s^* \left(1 - r_1^f \left(1 - \delta_s^m\right) - r_2^f \left(1 - \delta_2^m\right) + r_1^f r_2^f \left(1 - \delta_1^m - \delta_2^m + \delta_3^m\right) \right) := s^* \Delta_m \tag{60}$$

This pins down a ratio between the amount of wool and mutton in equilibrium given the various disease parameters. Note that since in equilibrium domestic animals have exactly the same infection rates as foreign animals, this ratio would be the same if calculated for total production (instead of just domestic). We define this ratio as $(w_d^*/m_d^*) = R$.

Next, we solve the firm's profit problem to get the price rule linking mutton, wool, and sheep prices.

$$\pi = p_m^T (m_d^* + m_f^*) + p_w^T (w_d^* + w_f^*) - p_s^T (s^* + s^f) \tag{61}$$

After substituting in the steady state values of mutton and wool, the profit function is simply a function of $s^* + s^f$. Maximizing with respect to total sheep yields the following relationship between prices:

$$p_s^T = \Delta_m p_m^T + \Delta_w p_w^T \tag{62}$$

Next, we turn to the optimal consumption equations for wool and mutton, defined in equation (57). Given these, and the ratio linking wool and mutton production $(w_d^*/m_d^*) = R$, market clearing would imply the following relationship:

$$\frac{w_t}{m_t} = R = \left(\frac{\alpha_3 I}{p_w^T} \right) \left(\frac{p_m^T}{\alpha_2 I} \right) \tag{63}$$

Substituting in the price rule from the firm's problem into this equation yields the following equilibrium prices for wool and mutton

$$p_m^T = \frac{R\alpha_2 p_s^T}{R\alpha_2 \Delta_m + \alpha_3 \Delta_w} \qquad\qquad p_w^T = \frac{\alpha_3 p_s^T}{R\alpha_2 \Delta_m + \alpha_3 \Delta_w} \tag{64}$$

Now we turn to the final prices that need to be determined: p_b^T, p_c^T. We start by deriving

the steady state amount of beef that is produced from the steady state number of cattle. Substituting the steady state number of healthy and infected cattle from equation (56) into the beef production technology in equation (14) yields the steady state amount of beef produced:

$$b_d^* = c^*\big(1 - r_2^f(1 - \delta_2^b)\big) \coloneqq c^*\Delta_c \tag{65}$$

Next, we solve the firm's profit problem to get the price rule linking beef and cattle prices.

$$\pi = p_b^T b_d^* - p_c^T c^* = p_b^T\big(c^*\Delta_c\big) - p_c^T c^* \tag{66}$$

Maximizing profits with respect to cattle yields the following rule between the price of cattle and the price of beef.

$$p_c^T = p_b^T \Delta_c \tag{67}$$

Since there is no trade in cattle, market clearing implies domestic beef production (b_d^*) is equal to domestic beef consumption defined in equation (57).

$$c^*\Delta_c = \frac{\alpha(AN + p_c^T c^* + p_s^T s^*)}{p_b^T} \tag{68}$$

Finally, this equation along with the price rule from the firm's problem provides a system of two equations that can be used to derive the prices of cattle and beef, which are given by the following equations.

$$p_b^T = \frac{\alpha_1(AN + p_s^T s^*)}{c^*\Delta_c - \alpha_1 c^*\Delta_c} \qquad\qquad p_c^T = \frac{\alpha_1(AN + p_s^T s^*)}{c^* - \alpha_1 c^*} \tag{69}$$

C.2 Welfare Assessment

Table B5: Parameter Choices for the Model Calibration

Parameter	Value	Source
α_1	.15	Perren (1978)
α_2	.15	Perren (1978)
α_3	.15	
α_4	.55	
σ	.3	
λ	.8	Figure B10
L, φ, A_t, N_t	1	
β	1	
p_{gt}	1	
p_ℓ^w	$.8p_\ell^a$	Harley (2008)
θ_1	.95	Figure B11
θ_2	.97	Figure B11
θ_3	.95	Figure B11
δ_2^b	.75	Young et al. (2013)
δ_1^m	.9	Young et al. (2013)
δ_2^m	.75	Young et al. (2013)
δ_3^m	.75	Young et al. (2013)
δ_1^w	.6	Rehbein et al. (2000)
δ_2^w	.9	Rehbein et al. (2000)
δ_3^w	.6	Rehbein et al. (2000)

Note: This table presents the values used for the parameters in the model when conducting the welfare analysis.

Figure B9: Diagram of Alternative Trade Scenarios Considered in the Welfare Analysis

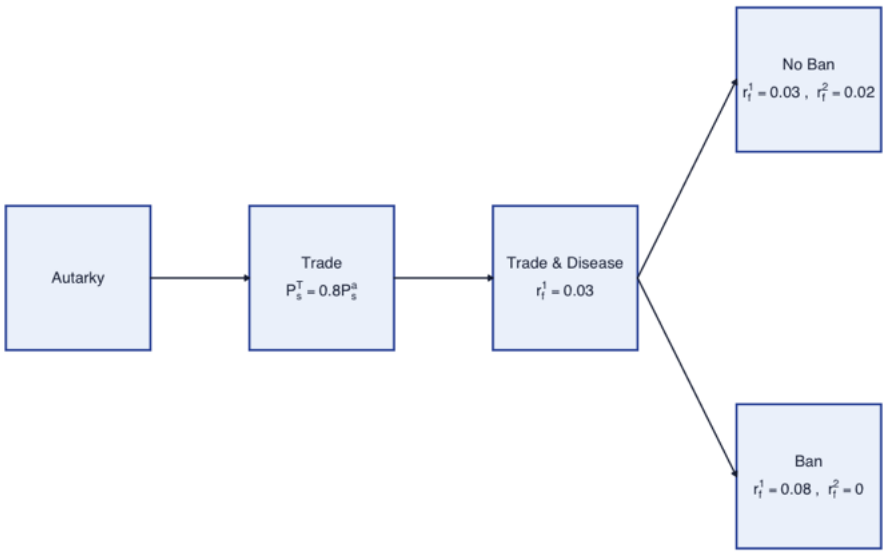


Figure B10: Relative Share of Domestic Sheep and Cattle to Inform λ



Note: This figure presents the share of total animals (both cattle and sheep) represented by sheep over time. This is used to inform λ in the model.

Figure B11: Data on Disease Infection and Mortality to Inform θ Parameters

A. Sheep Scab

TABLE

NUMBER of FARMS or other PLACES in the COUNTIES of GREAT BRITAIN upon which Fresh Outbreaks of Number of Sheep reported to have been Attacked, to have been Killed,

COUNTIES, &c.	Number of Counties reported from.	Number of Farms or other Places upon which Fresh Outbreaks took place.	Healthy Sheep on Infected Premises.		Attacked.	Diseased Sheep.		
			Slaughtered.	Removed.		Killed.	Died.	Recovered.
GREAT BRITAIN - -	65	2,412	584	2,089	*58,089	*385	779	39,638
ENGLAND - - - -	47	1,774	265	1,075	44,668	331	504	32,925
WALES - - - -	8	607	318	869	13,094	53	275	6,449
SCOTLAND - - - -	10	31	1	145	327	1	—	264

B. Foot-and-Mouth Disease

NUMBER of FARMS or other PLACES in the COUNTIES of GREAT BRITAIN upon which Fresh Outbreaks of occurred; with the Number of Animals reported to have been Attacked, to

COUNTIES, &c.	Number of Counties reported from.	Number of Farms or other Places upon which Fresh Outbreaks took place.	Number of Animals Attacked.							Diseased Animals.		
			Cattle.	Sheep.	Goats.	Swine.	Horses.	Other Animals.	Total.	Killed.	Died.	Recovered.
GREAT BRITAIN	92	52,164	519,523	116,546	250	54,931	5	310	691,565*	2,051*	5,853	633,084
ENGLAND - -	48	42,531	394,110	74,312	232	48,503	4	310	517,471	1,510	5,103	476,485
WALES - -	12	2,104	18,237	1,983	1	3,359	—	—	23,580	9	258	19,383
SCOTLAND - -	32	7,529	107,176	40,251	17	3,069	1	—	150,514	532	492	137,216

C. Rinderpest

—	Stock of Cattle enumerated 5th March 1866.	Summary from Commencement of the Disease to 31st December 1866.†							
		Farms, Sheds, &c. in which the Disease appeared.	Farms, &c. revisited by the Plague after having been free for 21 Days.	Cattle on Farms, Sheds, &c. where the Disease appeared.	Healthy Cattle Slaughtered to prevent the Spread of the Disease.	Number of Cattle Attacked by the Disease.	Diseased Cattle			
							Killed.	Died.	Recovered.	Unaccounted for.
GREAT BRITAIN	4,785,836	27,807	1,409	468,776	56,440	278,439	99,686	133,455	40,182	5,116
ENGLAND - -	3,270,299	22,917	1,195	375,530	40,529	221,121	91,874	97,747	27,717	3,783
WALES - -	578,136	896	54	13,307	721	9,359	1,261	6,567	1,192	339
SCOTLAND - -	937,401	3,994	160	79,939	15,190	47,959	6,551	29,141	11,273	994

Note: This figure presents data from historical reports on infections and mortality for the main diseases in the study. Panels A and B present data for sheep scab and foot-and-mouth disease. The data are taken from the 1871 edition of the *Annual Report of the Veterinary Department of the Privy Council*. Panel C presents data for rinderpest from *"The Report on the Cattle Plague in Great Britain, During the Years 1865, 1866, and 1867"*.